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A MODERN TRANSISTORIZED INSTRUMENTATION SYSTEM FOR ACOUSTICAL DATA ACQUISITION

by Wade D. Dorland, C. C. Thornton

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Bolt, Beranek and Newman, Inc.
Cambridge, Mass.

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TABLE OF CONTENTS

		Page
	SUMMARY	1
SECTION I.	INTRODUCTION	1
SECTION II.	OPERATIONAL REQUIREMENTS AND DESIGN GOALS	2
SECTION III.	DESIGN CONSIDERATIONS AND SYSTEM DESCRIPTION	4
SECTION IV.	PERFORMANCE CHARACTERISTICS	6
SECTION V.	COMPONENTS	9
	A. Microphone	9
	B. Preamplifier	12
	C. Decade Amplifier	13
	D. Transformers and Transmission Line	14
	E. Current Requirements	22
	F. Voltage Requirements	22
	G. Random Signal Considerations	23
	H. Line Amplifiers	25
	I. Signal Conditioning Circuit	28
SECTION VI.	PACKAGING, ADJUSTMENTS AND CONTROL CIRCUITS	29
	A. Field Unit	29
	B. Line Unit	29
	C. Signal Conditioning Unit	33
SECTION VII.	CONCLUSIONS	34
	REFERENCES	36

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Functional Diagram of Instrumentation System	5
2.	Electrical Frequency Response Characteristic for Entire Instrumentation System with One Mile of Field Wire	6
3.	Characteristic Electrical Noise Floor Spectrum For Entire Instrumentation System with One Mile of Field Wire. Shaded Area Indicates Range of Measurements on 14 Channels	7
4.	Typical Distortion Curve of Complete System with One Mile of Line (Without Signal Conditioning Unit)	7
5.	Typical Common Mode Rejection Characteristics	8
6.	Test Circuit For Measuring Common Model Rejection 20 Log E_1/E_2 of Complete Transmission System	9
7.	Response of C.I.C. Microphone, Type NM-135, S/N 351, From 0.1 cps to 50 cps	10
8.	Open-Circuit Response of C.I.C. Microphone Type NM-135. S/N 351, From 40 cps to 12 kcps	11
9.	Schematic of Microphone Preamplifier Circuit	12
10.	Schematic of Decade Amplifier Circuit	13
11.	Transformer Coupled Transmission Line with Floating Line Amplifiers	14
12.	Driving Point Impedance of No-Loss Transmission Line with $r_r = +1$ (Open Circuit)	16
13.	Transfer Function of No-Loss Transmission Line with $r_s = -1$ and $r_r = +1$	18
14.	Voltage Limitations of the Amplifier Driving a Transformer	23

LIST OF ILLUSTRATIONS (CONT'D)

Figure	Title	Page
15.	Sample Calculation of the Maximum RMS Voltage Which Can Be Transmitted by a Transformer. Given $E_{1\phi}$ = -5 DB	25
16.	Maximum RMS Voltage Which Can Be Transmitted by The Same Transformer For a Different Spectra (Second Sample Calculation)	26
17.	Schematic of Line Amplifier Circuit	27
18.	Schematic of Signal Conditioning Circuit	28
19.	Interconnection Diagram of Field Unit, MSFC-1162-T	30
20.	(A) View of Field Unit Showing Circuit Boards, Transformer, and Batteries; (B) Internal Wiring of Field Unit; (C) Bottom View of Field Unit Showing Complete Chassis; (D) Typical Field Installation	31
21.	Interconnection Diagram of Line Unit, MSFC 1162-R	32
22.	View of Line Assembly With Top Removed	33
23.	Signal Conditioning Amplifier Assembly With Top Removed	34
24.	Typical System Installation	35

LIST OF TABLES

Table	Title	Page
1.	Corrections, in DB, to Be added To the Sound Pressure Levels in One-Third Octave Bands Above 1 kcps	11

ACKNOWLEDGEMENT

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A MODERN TRANSISTORIZED INSTRUMENTATION SYSTEM FOR ACOUSTICAL DATA ACQUISITION

SUMMARY

Measuring the noise levels and spectra in the vicinity of large rocket engines and space vehicle boosters, and at distances up to about one mile during static testing, is one of the many responsibilities of the Acoustics Section of the Test Laboratory at Marshall Space Flight Center. To obtain data under a variety of climatic and field conditions with the necessary accuracy, reliability, and in a form readily accepted by existing data recording facilities, a new instrumentation system was designed, tested, and built.

The system consists of a microphone with a preamplifier followed by a step-attenuator and decade amplifier. For transmission of this signal to the recording facility, standard U. S. Army communications field wire is used instead of the conventional coaxial cable. Use of this field wire substantially reduces cost and results in substantially improved reliability and flexibility in field use. Special transformers and floating line amplifiers match the field wire transmission line to the decade amplifier at the input end and to a signal conditioning unit at the output end of the recording facility. All amplifiers use solid-state devices and the amplifiers in the field are battery operated.

The system is now in use and is performing in a satisfactory manner. The consideration leading to its design and its performance characteristics are described in detail in this report. Circuits, methods of packaging, and the results of tests on the system and its components are given. The design was evolved in close cooperation between the Acoustics Section of the Test Laboratory at Marshall Space Flight Center and Bolt Beranek and Newman Inc.

Dr. D. U. Noiseux's contributions to this project were supported by NASA Contract NAS8-5009 with Bolt Beranek and Newman Inc., Cambridge, Massachusetts, for which Mr. C. C. Thornton was Technical Administrator.

SECTION I. INTRODUCTION

The engineers responsible for measuring sound pressure levels and spectra during static testing of large rocket engines and space vehicle boosters are confronted with a difficult task. It is known that the noise spectrum encompasses the frequency range from less than 1 cps to over 10,000 cps and that overall noise levels as high as 160-165 db re 0.0002 microbar may be encountered in the vicinity of the rocket engines.

At the same time, the noise floor of the system must be low enough to permit a valid spectral analysis over the entire frequency range of the noise when measurements are made one-half mile or more from the test stand.

While the basic function of an acquisition system for acoustical data is very simple, there are many general requirements which the system must meet: the microphone must be stable, easily calibrated and resistant to weather, as must be the remainder of the system. The system must be easily installed, independent of external power sources, resistant to electrical and other interference, and easily adaptable to the varying requirements of any particular measurement program. It soon became clear that no commercially available system was capable of meeting these general requirements and that a design using solid state devices offered the best potential for achieving the operational goals. Therefore, a program was initiated to conceive, design, develop, fabricate, and test an acoustical instrumentation system that would take advantage of the latest developments in electronics and applied acoustics, while at the same time meeting the rigorous requirements of field use encountered in the operational support of static tests of rocket systems.

The result of this effort is a system which is now in use at MSFC for making the bulk of acoustical measurements during static tests of the Saturn vehicles and propulsion systems. Because the authors consider this system to have useful properties and because the concepts used in its design may be applicable to other situations, the system, its design objectives, and performance are described in detail in this report.

SECTION II. OPERATIONAL REQUIREMENTS AND DESIGN GOALS

In addition to meeting the general demands for stability, reliability, and flexibility, the following specific requirements were formulated for the system with a one-mile length of balanced line:

1. Maximum Overall RMS Sound Pressure Level

   165 db re 0.0002 microbar.

2. Frequency Range

   1 cps to 10,000 cps.

3. Maximum Overall Noise Floor (equivalent sound pressure level)

   80 db re 0.0002 microbar.

4. Overall Electrical Frequency Response

   Uniform within plus 0 minus 1 db re response at 1000 cps.

5. Dynamic Range (maximum RMS sinusoidal signal input re RMS noise floor)

   100 db min.

6. Nonlinear Distortion (at maximum RMS sinusoidal signal input)

   one per cent max.

7. Gain Adjustments:

   40 db in 10 db steps at sending and receiving ends for optimum performance for wide variety of test conditions.

8. Adequate Rejection of Common Mode Signals induced in the Line

9. Adequate Vibration Isolation

10. Adequate Damping of Transient Response

11. Power Supply

    Self-contained batteries; dry cell batteries in Field Unit; rechargeable batteries in line unit.

12. Remote On-Off Switching

13. Battery Life for Field Units

    250 days at 2 hours daily use; voltage drop not to exceed 1 volt.

14. Ambient Temperature

    0° F to 130° F.

15. Ambient Relative Humidity

    30 per cent to 100 per cent.

16. Weather Protection

    All parts of Field Unit, except microphone, housed in all-weather container.

17. Connectors

Simple and trouble-free connectors for signal and control wires.

18. Packaging

Modular construction for fast disassembly and assembly for maintenance.

19. Testing and Calibration

Appropriate test jacks and fixtures for field testing and calibration.

SECTION III. DESIGN CONSIDERATIONS AND SYSTEM DESCRIPTION

The Chesapeake Instrument Company Model NM-135 microphone has been in use for several years at Marshall Space Flight Center (MSFC) with good results. An acoustical calibrator has been developed for a quick check in the field of the acoustical sensitivity of the microphone at one frequency (400 cps). A survey of other available microphone units indicated the desirability of continued use of this unit. Hence, it was decided early in the program to design the system around the above microphone.

The basic function of the circuits is very simple: to furnish broad-band, noise-free amplification of the microphone output signal to a level and impedance appropriate for acceptance by a standard FM magnetic tape recorder of the instrumentation type. As already mentioned, standard U.S. Army field wire is to be used as a transmission line and flexibility in both gain adjustment and accommodation of varying line and microphone cable lengths are required to meet the varying conditions in the field. To render the circuits free from electrical interference from adjacent power sources, it is mandatory to use a balanced transmission line and, by employing transformers at both ends, to provide independent grounds at both the transmitting and receiving ends. To provide the necessary flat frequency response characteristics at the low frequencies, two basic approaches are possible:

1. Special line transformers with adequate low-frequency response and a floating solid-state power amplifier on the transmission line side.

2. Modulation and demodulation of the audio signal. For example, suppressed carrier modulation and demodulation at each end of the line to realize the equivalent of "DC transformers."

After thoroughly investigating the cost and the technical advantages of the two possibilities, Scheme 1 was adopted.

Figure 1 is a block diagram of the instrumentation system and its major components. The microphone is connected via a shielded microphone cable to a solid-state preamplifier which acts essentially as an impedance matching unit. To maintain adequate low-frequency response, the input impedance of the preamplifier must be of the order of several hundred megohms. The output impedance of the preamplifier is low enough to permit the use of a conventional attenuator. The attenuator has a 40-db range and is preset in the field according to the expected range of sound pressure levels. A decade amplifier with a fixed gain of 40 db follows, and is terminated into a coupling transformer specially designed for adequate low-frequency response and signal level handling capacity. It is carefully shielded and its secondary winding is balanced with respect to ground. A pair of battery-operated, floating, solid-state line amplifiers supply the necessary signal power to drive the field wire line at a maximum signal level of about 2 volts RMS. The electronics so far described comprises the Field Unit, which is placed in its weather-proof case in the vicinity of the microphone at the individual measurement positions.

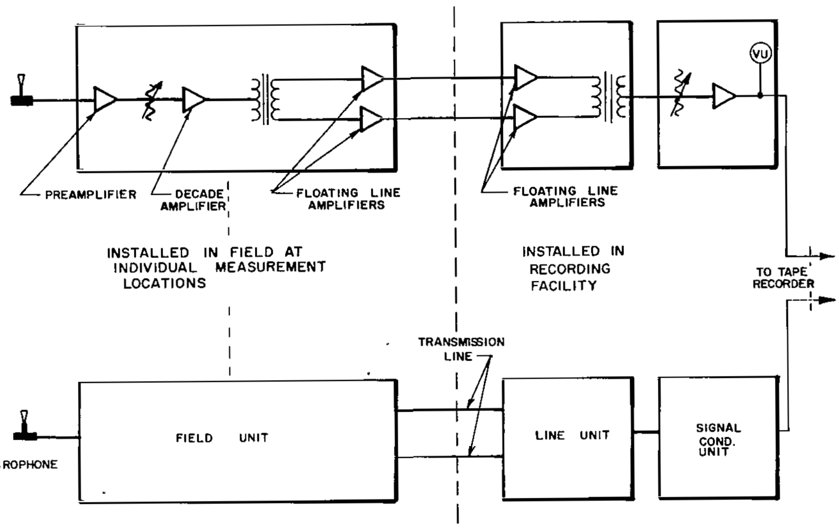


FIGURE 1. FUNCTIONAL DIAGRAM OF INSTRUMENTATION SYSTEM

To conserve signal power, the field wire transmission line is not terminated in its characteristic impedance at the recording facility, but is directly connected into a pair of floating line amplifiers with high input impedance. At the output of these amplifiers there is another coupling transformer to isolate the line from the rest of the equipment and maintain electrical balance. These components comprise the Line Unit; they are identical with their counterparts in the Field Unit.

The output of the Line Unit is connected to the Signal Conditioning Unit which contains a step-attenuator, a buffer amplifier, and a VU meter. Its purpose is to measure and adjust the signal level for best use of the available dynamic range of the tape recorder units, on which the signal is recorded to be analyzed later.

Line and Signal Conditioning Units are rack-mounted in groups of seven in the Central Recording Facility. The line amplifiers in the Line Unit are operated from rechargeable nickel-cadmium batteries; the power to the Signal Conditioning Units is supplied by conventional power supply units. There are additional test and control circuits which will be described later.

SECTION IV. PERFORMANCE CHARACTERISTICS

Before proceeding with the detailed description of the components of the system, it is appropriate to present typical data describing the overall performance of the system.

Figure 2 shows the overall electrical frequency response characteristic of the system with one mile of line. The shaded area indicates the spread observed in 14 systems (channels). It is seen that some channels somewhat exceed the specified response deviation of -1 db at the very low frequencies.

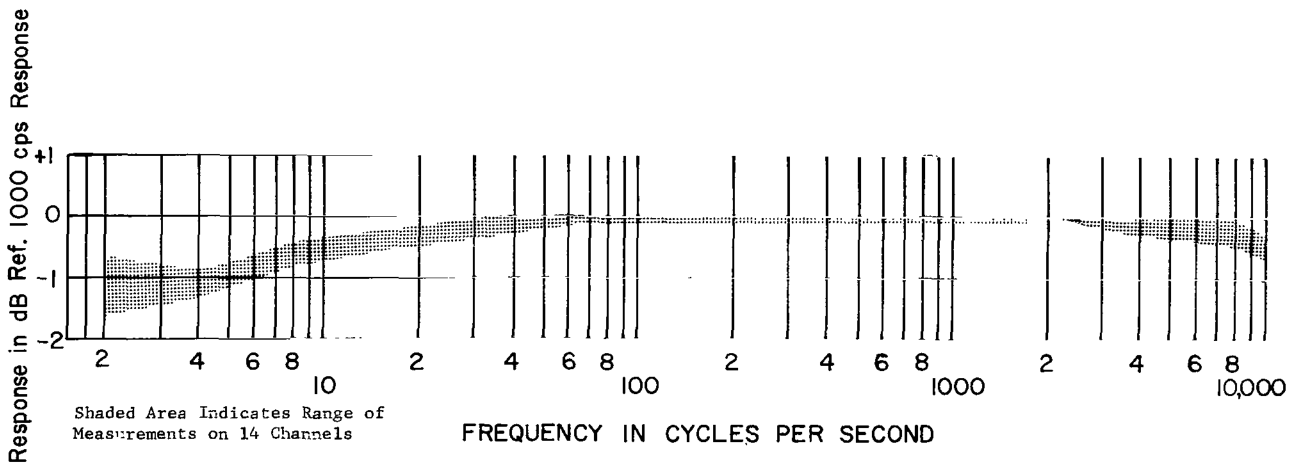


FIGURE 2. ELECTRICAL FREQUENCY RESPONSE CHARACTERISTIC FOR ENTIRE INSTRUMENTATION SYSTEM WITH ONE MILE OF FIELD WIRE.

The noise floor of the entire system measured in octave bands is shown in Figure 3. For these data the microphone and microphone cable were replaced by a dummy capacitor of 2000 pf. The shaded area indicates the spread observed in 14 systems. It is seen that the overall noise floor is below the maximum specified value of 80 db re 0.0002 microbar in all cases.

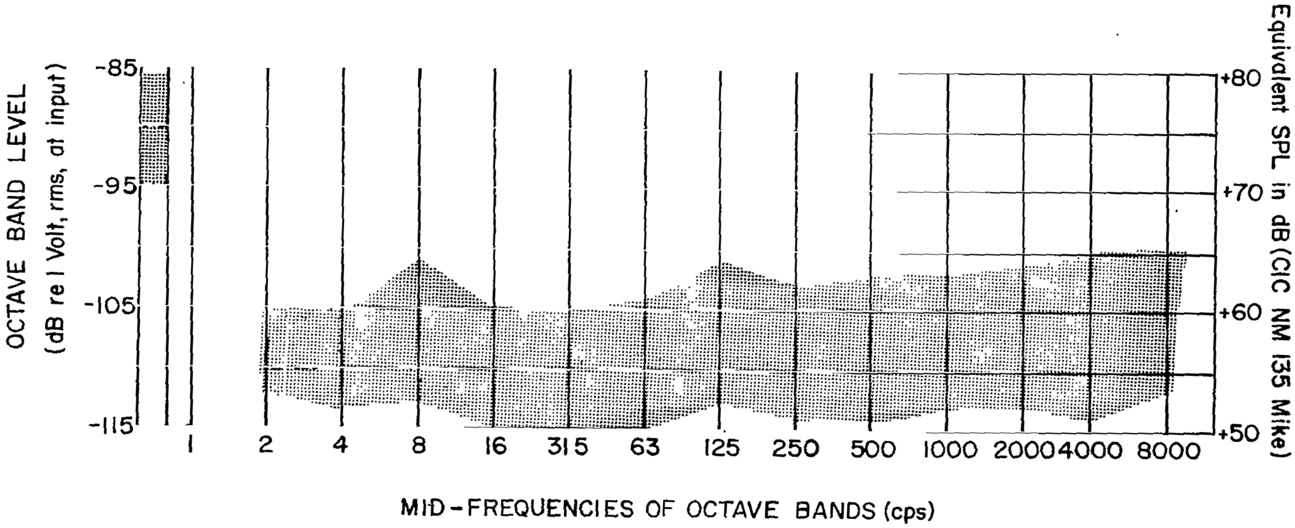


FIGURE 3. CHARACTERISTIC ELECTRICAL NOISE FLOOR SPECTRUM FOR ENTIRE INSTRUMENTATION SYSTEM WITH ONE MILE OF FIELD WIRE. SHADED AREA INDICATES RANGE OF MEASUREMENTS ON 14 CHANNELS

Figure 4 shows the non-linear distortion characteristics for a typical system without the Signal Conditioning Unit. It is seen that the design objective of less than one per cent distortion is achieved for a maximum sinusoidal RMS output of about + 8 dbv. This is adequate for driving the Signal Conditioning Unit to yield 1 volt output voltage to the tape recorder.

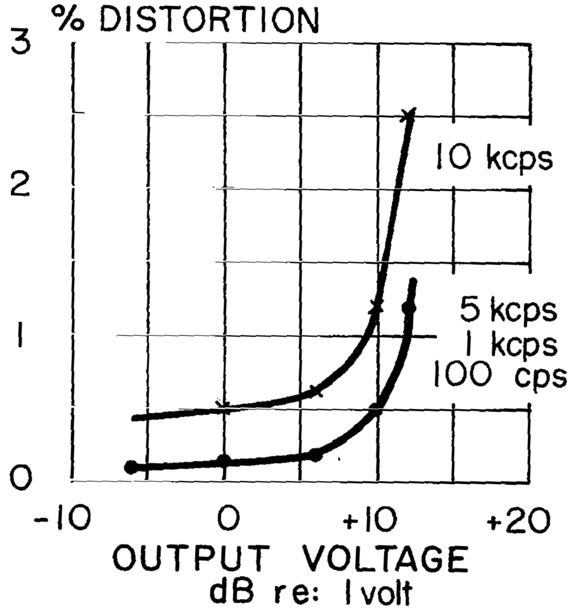


FIGURE 4. TYPICAL DISTORTION CURVE OF COMPLETE SYSTEM WITH ONE MILE OF LINE (WITHOUT SIGNAL CONDITIONING UNIT)

Figure 5 shows measured data on common mode rejection obtained on the prototype of the system.

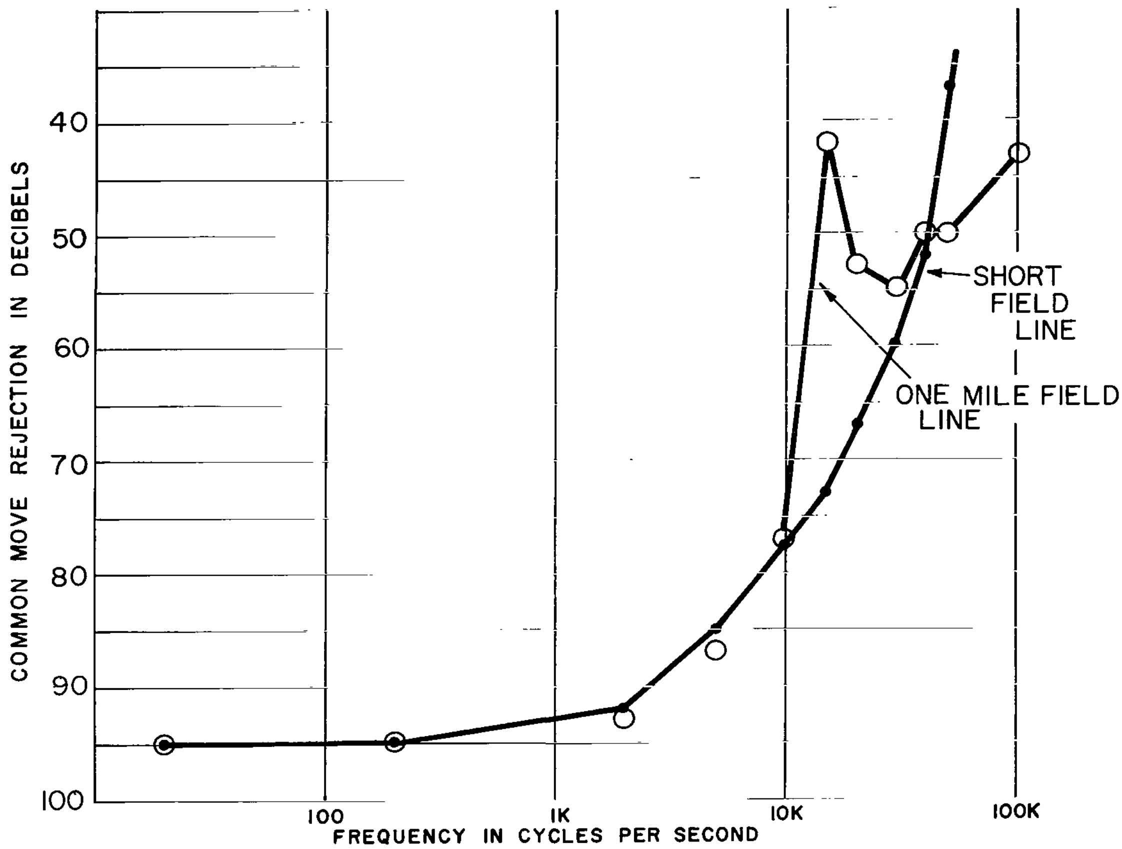


FIGURE 5. TYPICAL COMMON MODE REJECTION CHARACTERISTICS

The data were obtained with the test circuit shown in Figure 6. It is seen that the output voltage due to a common-mode signal source (a source which drives both conductors of the transmission line essentially in phase relative to ground) is at least 75 db below the voltage level of that source.* The common mode rejection at low frequencies is about 95 db.

* A balancing circuit (Section VI) has been incorporated into the final design; this results in even better common mode rejection at the high frequencies.

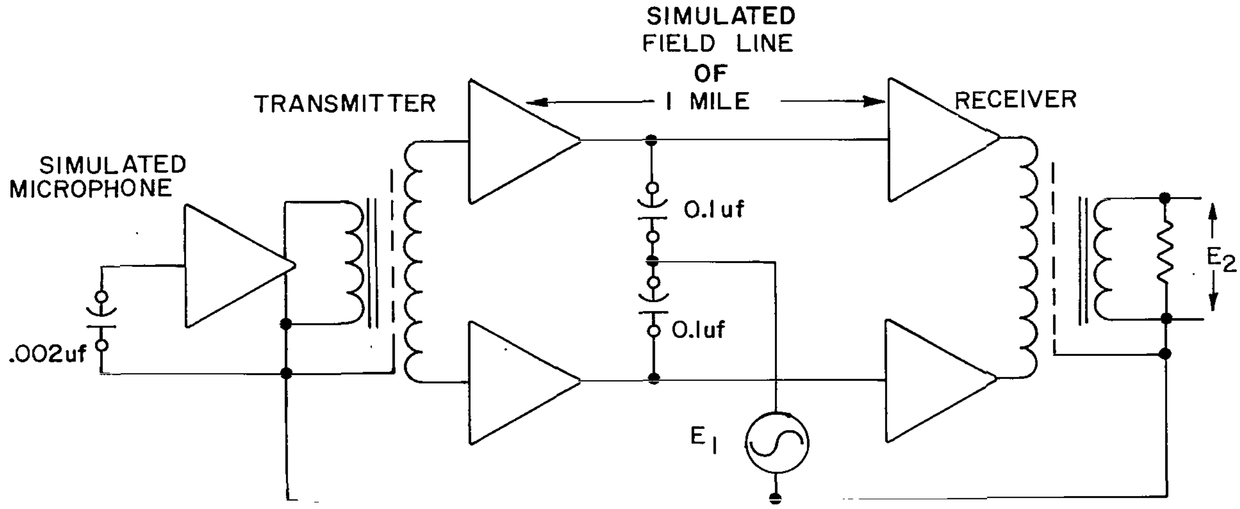


FIGURE 6. TEST CIRCUIT FOR MEASURING COMMON MODEL REJECTION 20 LOG E_1/E_2 OF COMPLETE TRANSMISSION SYSTEM

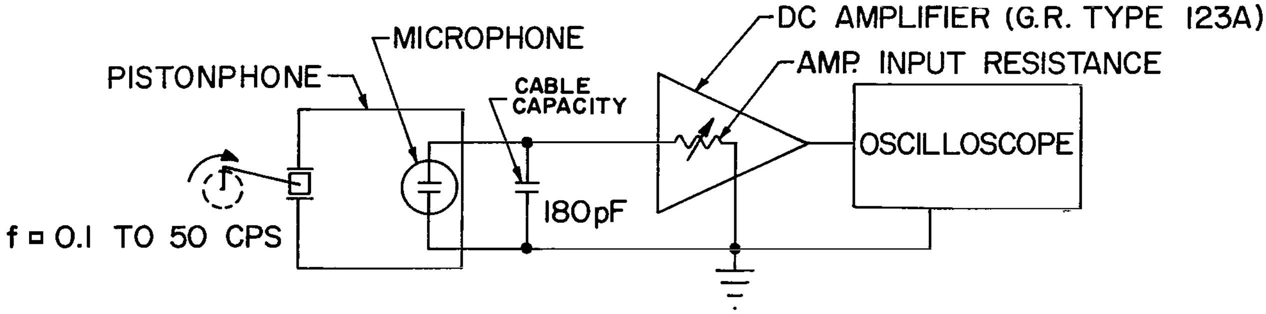
SECTION V. COMPONENTS

In this Section the major components of the system and their characteristics will be described in detail.

A. MICROPHONE

The microphone is a modified hydrophone, Model NM-135, manufactured by the Chesapeake Instrument Company. This microphone consists of a self-generating, peizoelectric sensing element which is sealed against precipitation and water vapor leakage; it is mounted on a vibration isolating base, and has its signal output through a BNC coaxial connector. Its dynamic range is rated to cover a range of sound pressure levels from 80 to over 180 db re 0.0002 microbar. The microphone sensitivity is nominally -94 db re 1 volt per microbar. Its nominal internal capacity is 1600 pf.

To evaluate the low-frequency behavior of this microphone, a constant sound pressure level was generated by means of a pistonphone in the frequency range of 0.1 to 50 cps. The cavity of the pistonphone was large enough to insure that the transition from adiabatic to isothermal behavior of the gas in the cavity occurs well below 0.1 cps. The test setup is shown in the upper half of Figure 7. By varying the input resistance of the amplifier, the response of the microphone-amplifier combination at low frequencies could be determined. The tests showed that the open-circuit response of the microphone is uniform down to below 0.1 cps. Hence acoustic leakage through the sensitive elements of the microphone is negligible, at least down to 0.1 cps. When connected to an amplifier of a given input resistance, the response of the combination is determined only by the microphone and cable capacitance and the input resistance of the amplifier. This is shown by the curves in the lower half of Figure 7. The response calculated from the



TEST SETUP

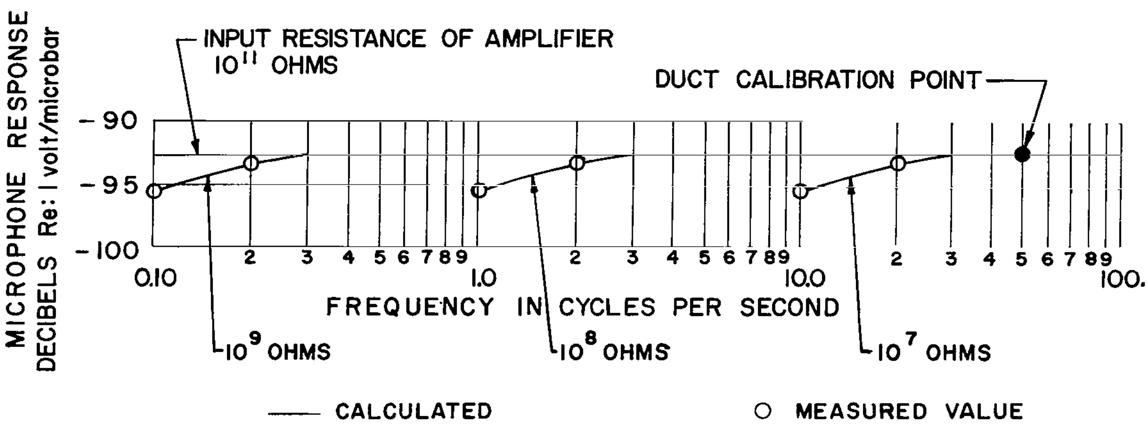


FIGURE 7. RESPONSE OF C.I.C. MICROPHONE, TYPE NM-135, S/N 351, FROM 0.1 CPS TO 50 CPS

known values of capacitance and resistance accounts for the observed drop in response. Since the input resistance of the preamplifier used in the present system is 3 X 10^8 ohms (see below), the drop of the response at 1 cps is less than 1 db. Appropriate corrections to account for this can easily be applied, if desired. The result of a calibration of this particular microphone carried out in a plane wave tube at 50 cps is shown in the graph as a solid point.

The open-circuit voltage calibration of a typical microphone at higher frequencies is shown in Figure 8. The data were obtained in a plane wave tube below 600 cps and above that frequency in an anechoic chamber. The angle of incidence of the sound field with respect to the axis of the microphone was 90 degrees in the anechoic room. In the plane wave tube the angle of incidence was not important because the directivity of this microphone is negligible below about 1000 cps. The data show that there is a gradual drop in sensitivity above 1 kcps. The data shown in Figure 8 were obtained using single frequencies. To obtain appropriate corrections for the deviations of the free-field response of the NM-135 microphone from uniformity above 1 kcps, a number of microphones were tested in a free field and appropriate corrections for use with one-third octave band data was obtained. Table I shows these corrections obtained from measurements on 20 microphones. These corrections are added to the sound pressure levels in one-third octave bands obtained upon analysis of the data recorded from this system. The data show that for frequencies below 4 kcps corrections less than 2 db apply.

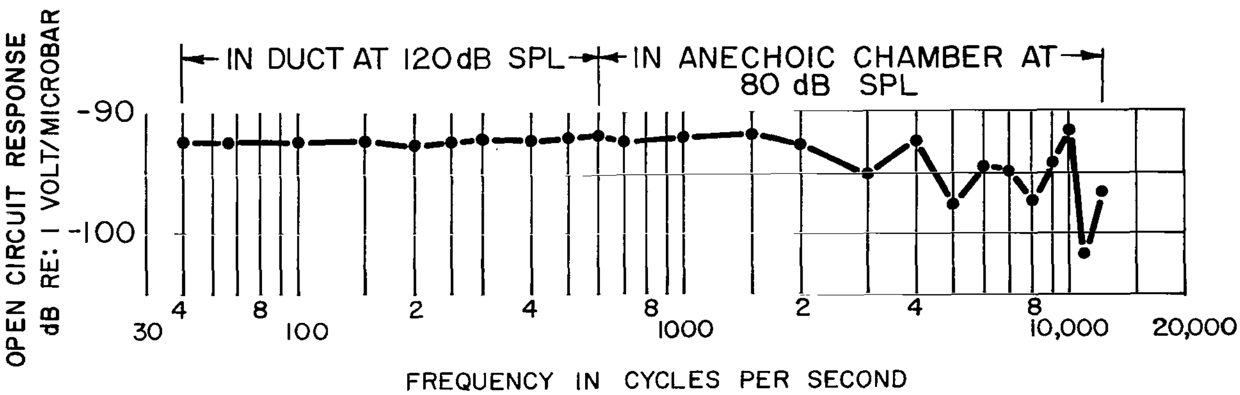


FIGURE 8. OPEN-CIRCUIT RESPONSE OF C.I.C. MICROPHONE TYPE NM-135, S/N 351, FROM 40 CPS TO 12 KCPS

TABLE 1

CORRECTIONS, IN DB, TO BE ADDED TO THE SOUND PRESSURE LEVELS IN ONE-THIRD OCTAVE BANDS ABOVE 1 KCPS

Center Frequency of One-Third Octave Band cps	Correction, db
1250	0
1600	+0.5
2000	+1.0
2500	+1.75
3200	+1.5
4000	+1.25
5000	+3.25
6300	+2.0
8000	+3.0
10,000	+4.0

B. PREAMPLIFIER

The microphone preamplifier, whose circuit diagram is shown in Figure 9, has, effectively, unity voltage gain. A field effect transistor (C622) supplies the required high input impedance which is limited to 300 megohms by a physical resistor connected across the input terminals. The input shunt capacitance is approximately 30 pf. The complete circuit gives a very low output impedance because of inverse feedback to the input transistor

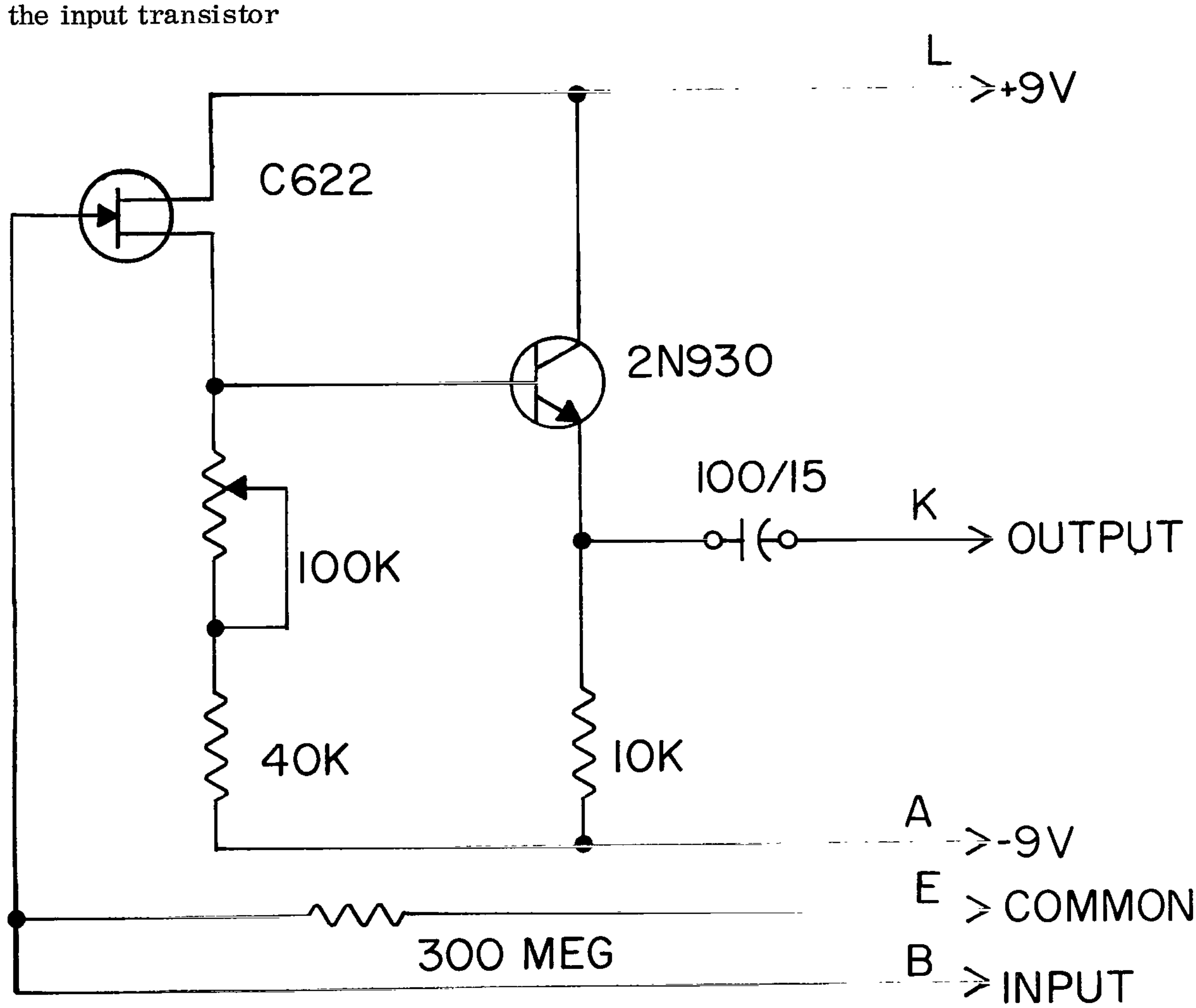


FIGURE 9. SCHEMATIC OF MICROPHONE PREAMPLIFIER CIRCUIT

The maximum input (and output) sine wave voltage is approximately 3 volts RMS. With the CIC NM-135 microphone, this voltage corresponds to a sinusoidal sound pressure level of 178 db SPL. Since rocket noise does not exceed about 165 db SPL overall even in the near field, such noise can be measured safely with the microphone-preamplifier combination within peak factors of at least 15 db.*

The preamplifier with a 2000 pf capacitor connected at the input (to simulate the microphone and its cable) performed satisfactorily up to an ambient temperature of at least 130° F.

The noise floor of the preamplifier is effectively that of the complete system.

C. DECADE AMPLIFIER

To amplify the signal level from the output of the transducer preamplifier, and to drive the interstage transformer at the transmitting end of the line, a decade amplifier was incorporated into the system. This amplifier is preceded by a 40 db attenuator which is adjustable in 10 db steps. The circuit diagram is given in Figure 10.

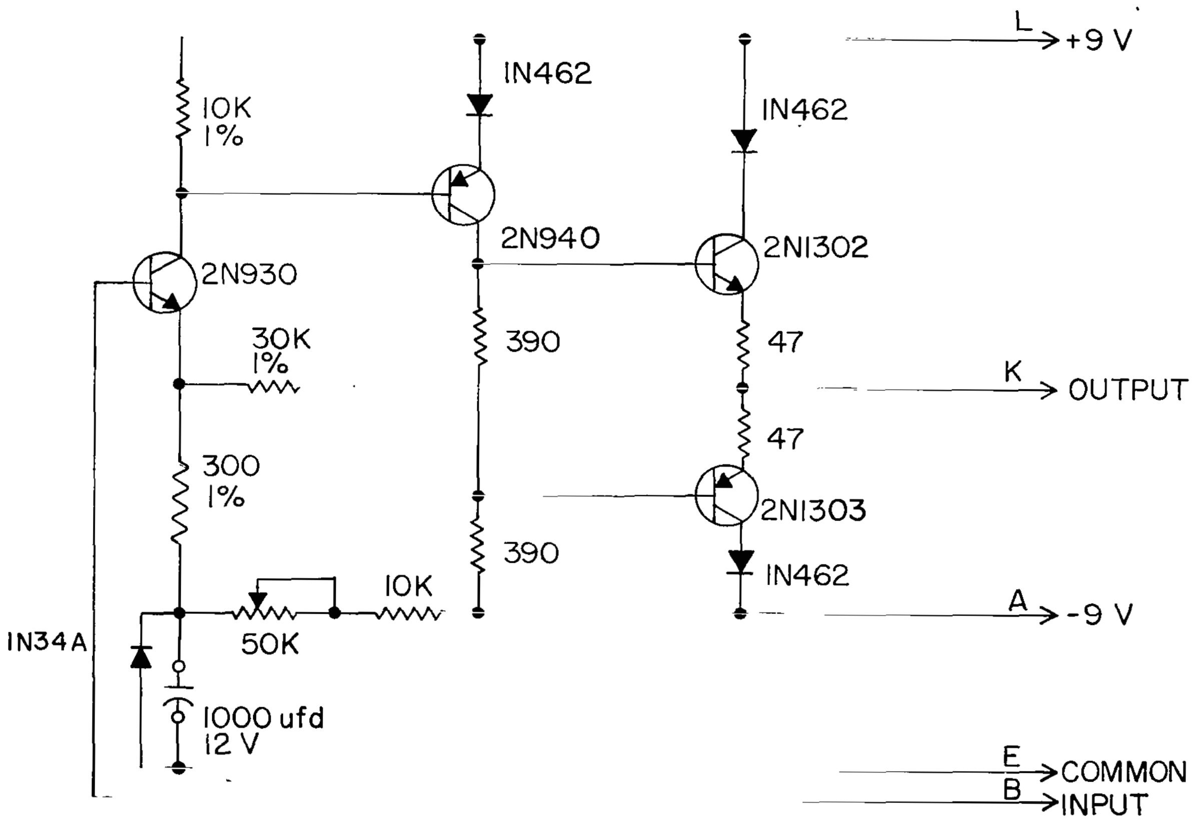


FIGURE 10. SCHEMATIC OF DECADE AMPLIFIER CIRCUIT

* This 15 db peak-to-RMS ratio allows for all but the most infrequent peaks in rocket noise.

A conventional transistor voltage amplifier is followed by a complementary transistor pair which furnishes the output signal to the coupling transformer (see below) and transmission line. Tests at elevated temperatures dictated that the first two transistors should be of the silicon type, with 2N930 and 2N940 being the actual transistor types chosen. The complementary transistor pair 2N1302 and 2N1303, while germanium, have performed well during the temperature tests because they operate as emitter followers, and their power dissipation is much below their rated value even at 125° F.

Since the transformer is used under the unusual conditions of very low frequencies and large impedance mismatch, it is important that limitations of the decade amplifier-transformer combination be carefully analyzed to determine the maximum overall RMS voltage which can be transmitted by the system, shown schematically in Figure 11.

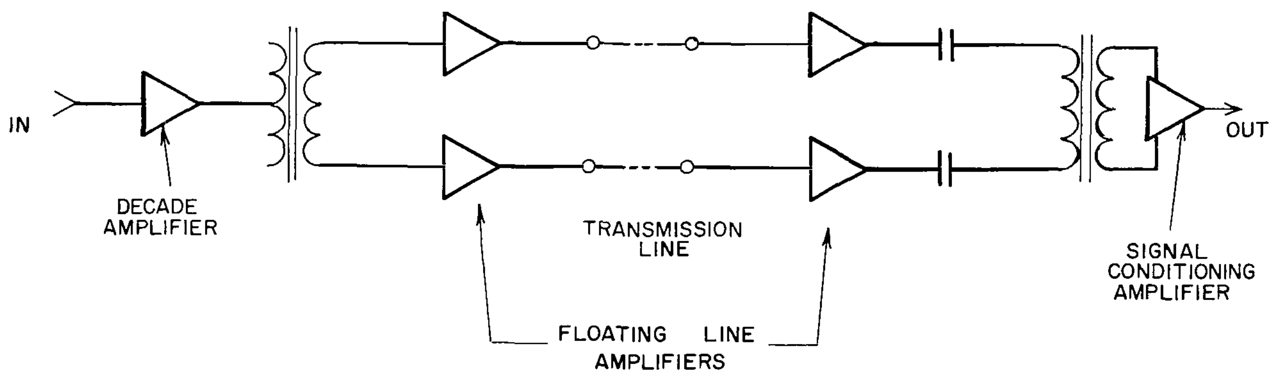


FIGURE 11. TRANSFORMER COUPLED TRANSMISSION LINE WITH FLOATING LINE AMPLIFIERS

Limitations apply to the maximum peak voltage and current which the amplifier can supply and also the maximum peak magnetic flux of the transformer. The maximum peak voltage E_{1m} which the decade amplifier can supply is limited by the type of transistors used and by the battery supply voltage. It is equal to approximately half of the total battery voltage; its exact value is obtained experimentally. The maximum peak current I_{1m} is limited by the dissipation of the output transistors of the decade amplifier. This limitation also imposes restrictions on the circuit design. Again I_{1m} is obtained experimentally.

For the circuit shown in Figure 10, E_{1m} and I_{1m} were found to be approximately 8 volts and 10 ma. The question of limitation by magnetic flux is discussed in detail in the paragraphs below.

D. TRANSFORMERS AND TRANSMISSION LINE

A transmission system was required that could transmit the signals over several thousand feet of transmission line. Field telephone lines, i.e., a pair of twisted wires, are much less expensive than coaxial cables or shielded lines which might otherwise be used. Cables are often damaged before or during a test (by brushfires, trucks, tractors, lawn mowers, ditch diggers, etc.). Since open lines could pick up signals induced from adjacent electrical power sources, it is mandatory to obtain a well balanced line with independent grounds for the transmitting end and the receiving end. This problem is complicated by the need to transmit a very broad frequency range, ranging from 1 cps to 10,000 cps. Since transformers must be used to obtain separate grounds, the transmission limitations of transformers at low frequencies are important, and were investigated in detail.

The field telephone line (WD-1/TT) considered for the signal transmission has a capacity of 0.06 microfarad per mile and a characteristic impedance Z_0 of approximately 100 ohms. Matched termination of this transmission line by its characteristic impedance would be a waste of power. A large mismatch in the line termination is acceptable and efficient if the line length is restricted to one mile or less. The following analysis, based on a no-loss line, describes this approach.

If the line is left open-circuited at the receiving end, the driving point impedance Z_1 of the line at the transmitting end is:*

$$Z_1 = -j Z_0 \cot k\ell \tag{1}$$

where $k = \frac{2\pi f}{c}$

$c = 3 \times 10^8$ m/sec

ℓ = length of the line in meters

Z_0 = characteristic impedance.

A plot of $|Z_1/Z_0|$ is shown in Figure 12. Some numerical values are given which apply for $\ell = 1$ and 2 km and f = 10 and 20 kcps.

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* See any standard text on transmission line theory, e.g., E. A. Guillemin, Communication Networks II, John Wiley and Sons, Inc., 1951.

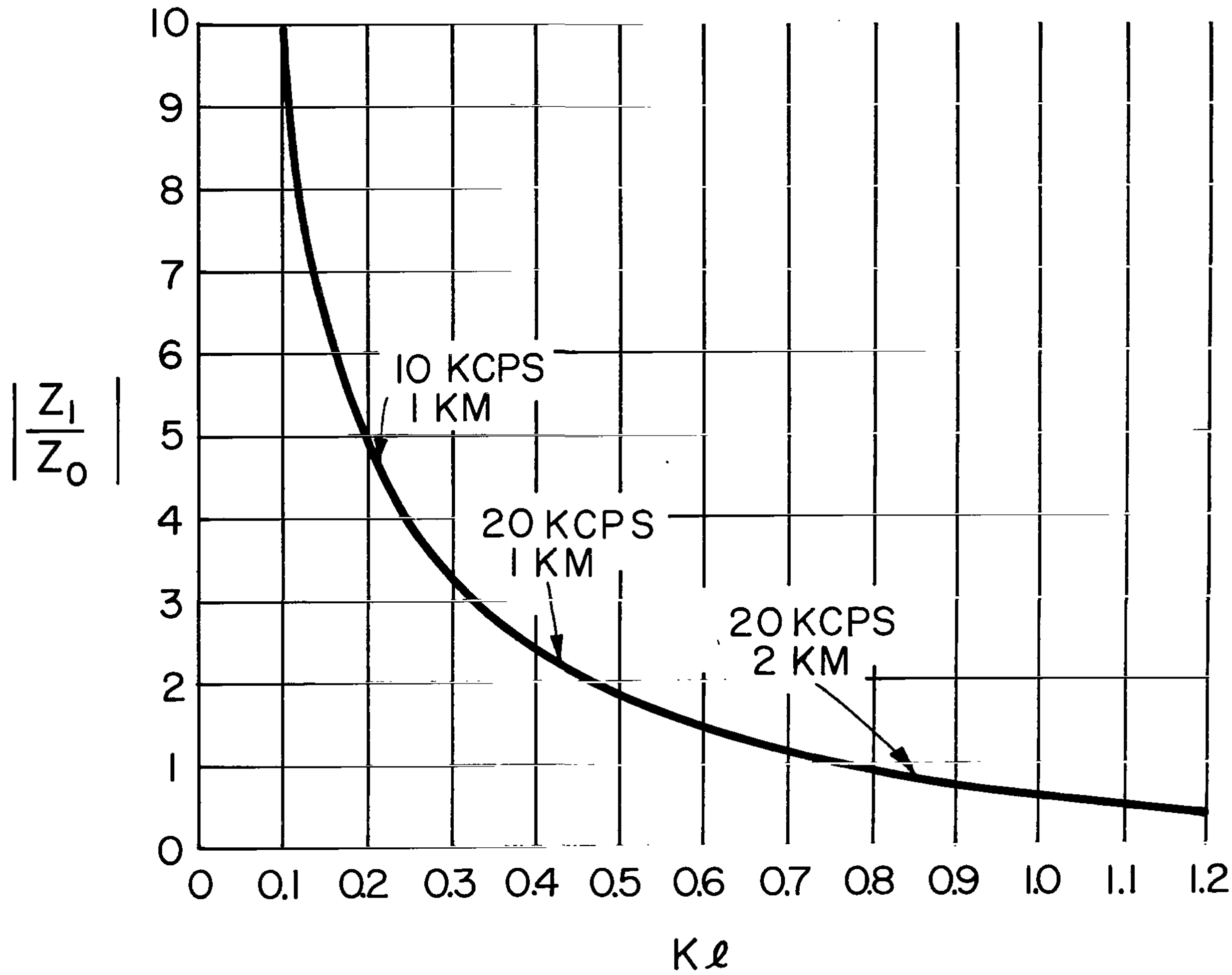

FIGURE 12. DRIVING POINT IMPEDANCE OF NO-LOSS TRANSMISSION LINE WITH r_r = +1 (OPEN CIRCUIT)

The transfer function of a no-loss transmission line is given by:

$$\frac{E_{out}}{E_g} = \frac{Z_o}{Z_s + Z_o} \cdot \frac{1 + r_r}{(e^{jk\ell} - r_s \cdot r_r \cdot e^{jk\ell})} \qquad (2)$$

$$r_r = \frac{Z_r - Z_o}{Z_r + Z_o} \qquad (3)$$

$$r_s = \frac{Z_s - Z_o}{Z_s + Z_o}$$

where

E_g = source voltage (emf)

E_r = output voltage across Z_r

Z_s = source impedance

Z_r = load impedance

r_s = reflection coefficient at source end

r_r = reflection coefficient at receiving end.

For open-circuit conditions, $r_r = +1$. If the source impedance z_s is made equal to Z_o, we get $r_s = 0$, giving

$$\frac{E_{out}}{E_g} \doteq e^{-jk\ell} , \tag{4}$$

which corresponds to a simple delay without attenuation.

If we were to let $Z_r = Z_o$ at the receiving end, we would obtain, with $r_r = 0$ and $r_s = 0$,

$$\frac{E_{out}}{E_g} = \frac{1}{2} \quad e^{-jk\ell} \quad . \tag{5}$$

It is clear that for a no-loss line, choosing $Z_s = Z_o$ and $Z_r = \infty$ is desirable. This arrangement increases the transmission E_{out}/E_g by a factor of 2 in comparison with a line terminated by its characteristic impedance. In practice however, the losses of the line would justify some mismatching (i.e., $Z_s < Z_o$) at the transmitting end to improve the transmission at high frequencies.

It is instructive to investigate the transfer function for open-circuit conditions at the receiving end and extreme mismatch at the sending end, i.e., $Z_s = 0$, or $r_s = -1$. From Equation (2) it follows that

$$\frac{E_{out}}{E_g} = \frac{1}{\cos k\ell} \quad . \tag{6}$$

The quantity 20 $\log_{10}$ (E_{out}/E_g) is plotted in Figure 13. Note that for the maximum frequency range (f $\lessdot$ 10 kc) and line lengths ($\ell \lessdot$ 1.6 km) of interest here, $k\ell \lessdot$ 1/3 and the increase in the transfer function is 1 db or less.

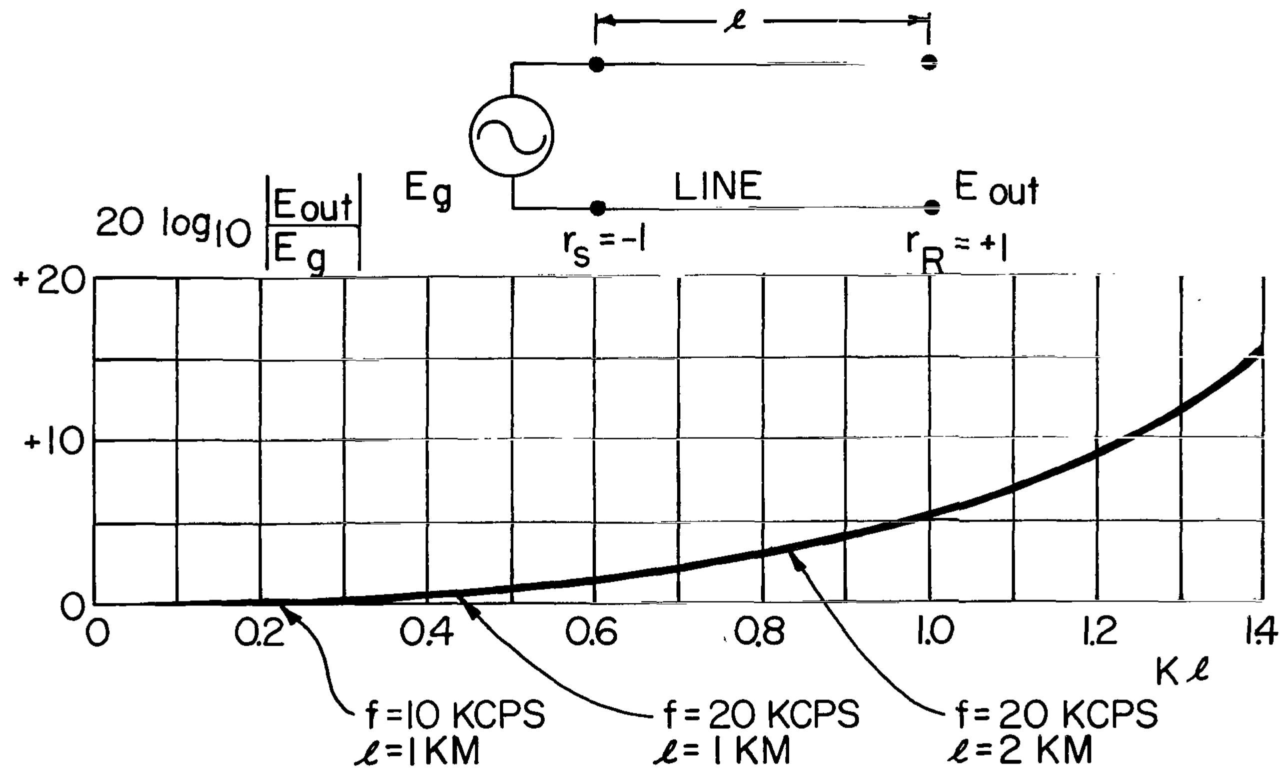

FIGURE 13. TRANSFER FUNCTION OF NO-LOSS TRANSMISSION LINE WITH r_s = -1 AND r_r = +1

Since the impedance termination Z_r of the line at the receiving end should satisfy the condition $Z_r >> Z_o$, and must take the form of a transformer to provide ground isolations, it is clear that excessively large inductance values of the transformer would be required at low frequencies. At high frequencies these large values of inductance would introduce correspondingly large shunt capacities which would limit both the high frequency response and the common mode rejection.

A practical solution is obtained, as shown in Figure 11, where the transformers at each end of the line are isolated by small battery-operated line amplifiers (push-pull complementary emitter followers) which supply the necessary power at the sending end. The transformers thus act only as voltage transformers since they are not required to supply any appreciable load current. In addition, the transformers are isolated from the large change of line impedance already shown in Figure 12. Moreover, the line amplifiers provide the desirable small source impedance for driving the transmission line. These amplifiers and their design will be discussed in detail in the following sub-section.

Having discussed the transmission line and termination problems, it is now possible to turn our attention to the design and performance requirements of the coupling transformers. Identical transformers are used at the transmitting and receiving ends of the transmission line; they provide ground isolation as well as balanced termination. They are special transformers designed for this application with the core size and the primary inductance and resistance selected to satisfy the low frequency requirements (R/L ratio) and the level of signal to be transmitted. But an upper boundary was set to the inductance value to limit capacity coupling between the primary and secondary windings. This capacitative coupling is further reduced by an electrostatic shield which isolates the secondary winding from the primary and the core. In operation, the core and the shield are connected to the transmitter, or receiver, ground. A turn ratio of 1:2 is used.

The operating conditions are such that the transformer secondary is essentially open circuited while the primary is driven from a low-impedance source. The low-frequency cutoff frequency f_ℓ (3-db point) is then determined essentially from the ratio

$$f_\ell = \frac{R}{2\pi L} \quad , \tag{7}$$

where L is the open circuit inductance of the primary winding and R is the total resistance in the primary loop including the winding resistance. For a conservative value of R = 100 ohms and for $f_\ell = 0.5$ cps, L becomes approximately 30 henries. The value of the primary current for 1 volt RMS at 1 cps is then only 6 ma. These values are easily realized.

The core size and the number of turns of the transformer are obtained from the usual transformer equations:

$$L = \frac{N^2 \, A \, \mu_o K}{\ell} \quad \text{henries} \tag{8}$$

$$\left.\begin{aligned} E_{peak} &= N \, 2\pi f \; A \; B_{peak} \quad &\text{volts} \\ &= N \, 2\pi f \; \phi_{peak} \quad &\text{volts} \end{aligned}\right\} \tag{9}$$

where

N = number of turns on the primary winding

B = flux density in webers/m^2

ϕ = flux in webers

A = cross section of the magnetic core in m^2

μ_o = permeability of air = $4\pi \times 10^{-7}$

K = relative permeability of the magnetic material

ℓ = length of the magnetic core in meters.

By imposing $B_{peak} = 1$ weber/m^2, $K = 10^4$, and imposing $E_{peak} = 1$ volt at f = 1 cps, we obtain a set of possible solutions.

A special transformer, designated BBN-1, was designed, incorporating these requirements, including those of electrostatic shielding and balanced construction.

The final model of the transformer had these characteristics:

1. Turns ratio	1:2
2. Primary	(Center tapped)
DC resistance	80 ohms
Inductance at one volt RMS, at stated frequencies	1 kcps: 44 henries
	60 cps: 50 henries
	10 cps: 100 henries
3. Secondary	(Center tapped)
DC resistance	420 ohms
4. Case	Steel, MIL-T27-A Style AJ case
Weight	11 ounces
5. Magnetic Shielding	Shielding provided by the steel case.
6. Electrostatic Shielding	The secondary winding is shielded from the primary winding and the core by a solid copper sheet.

7. Maximum Flux Linkage, limited by magnetic saturation at primary side	1 volt peak/cps at 3 per cent distortion
8. Frequency Response	1 cps to 20,000 cps within ±0.2 db
9. Linearity	Within ±1/2 db at 1 cps from 0.7v peak of a sine wave to at least 60 db down (0.0007v peak)
10. Common Mode Rejection	70 db down at 10 kcps and at least 80 db at the low frequencies

The data on linearity and frequency response were obtained with a small source impedance (about 50 ohms) and a large terminating impedance (about 30k ohms) simulating representative operating conditions.

The test for common mode rejection is basically the same as that discussed earlier for the complete system in connection with Figure 6. It consists of an arrangement whereby both ends of one winding are driven in phase with respect to ground. The output voltage across the other winding is observed. For perfect symmetry, it should be zero. In practice it is finite because of asymmetrical capacity coupling between windings. The tests showed adequate common mode rejection.

The considerations concerning the maximum peak voltage (for a given distortion level) are of particular interest. If this voltage is measured and plotted as a function of frequency, a substantially linear function of frequency results. This follows from Equation (9).

The slope E_{peak}/f of this line is a direct measure of the maximum flux linkage $N\phi_m$ for the particular transformer as shown by Equation (9). Data obtained for the BBN-1 unit showed $E_{max}/f \doteq 1$ volt per cycle. This is a characteristic quantity for a given transformer design. When one considers the fact that the signal is wide-band random noise with a peak factor of approximately 15 db, the maximum value of flux linkage becomes an important limitation of the maximum low-frequency signal which can be transmitted through the transformer without appreciable distortion. These and other limitations will now be considered in detail.

If one considers a transformer terminated essentially into open-circuit and driven by a low-impedance amplifier,* the following limitations on the maximum signal level apply:

---

* This condition applies to the decade amplifier driving the input transformer (to the line) and the two line amplifiers driving the output transformer (from the line) in the system under consideration.

a. A maximum voltage E_{1m} which can be supported by the amplifier,

b. A maximum current I_{1m} which can be supplied by the amplifier,

c. A maximum magnetic flux ϕ_m which can be accommodated by the transformer.

E. CURRENT REQUIREMENTS

The current I_{1m} which is supplied by the amplifier need not be appreciably larger than that imposed by the core saturation.

The flux limited current $I_{1\phi}$ is:

$$I_{1\phi} = \frac{N\phi_m}{L} = \frac{\frac{E_{1\phi}}{f}}{2\pi L} . \tag{10}$$

The peak current which the amplifier must supply should exceed $I_{1\phi}$;

$$I_{1m} \geq \frac{\frac{E_{1\phi}}{f}}{2\pi L} . \tag{11}$$

As an example we may consider a transformer specified by the following parameters:

R = 125 ohms

L = 50 henries

$\frac{E_{1\phi}}{f}$ = 0.6 volt peak per cycle.

The peak current which the amplifier must supply is given by Equation (11). In the present example $I_{1m} \geq 2$ ma peak.

The frequency f_ℓ at which the response is down by 3 db is about 0.4 cps according to Equation (7). This sets the lower limit of the operating frequency range with uniform response to about 1 cps.

F. VOLTAGE REQUIREMENTS

The voltage E_1 which can be transmitted by the transformer is limited at low frequencies by the maximum flux linkage $E_{1\phi}/f$ and at all frequencies by the maximum voltage E_{1m} of the driving amplifier. It is assumed, of course, that the current requirements set by Equation (11) have been satisfied. These limitations are illustrated in Figure 14.

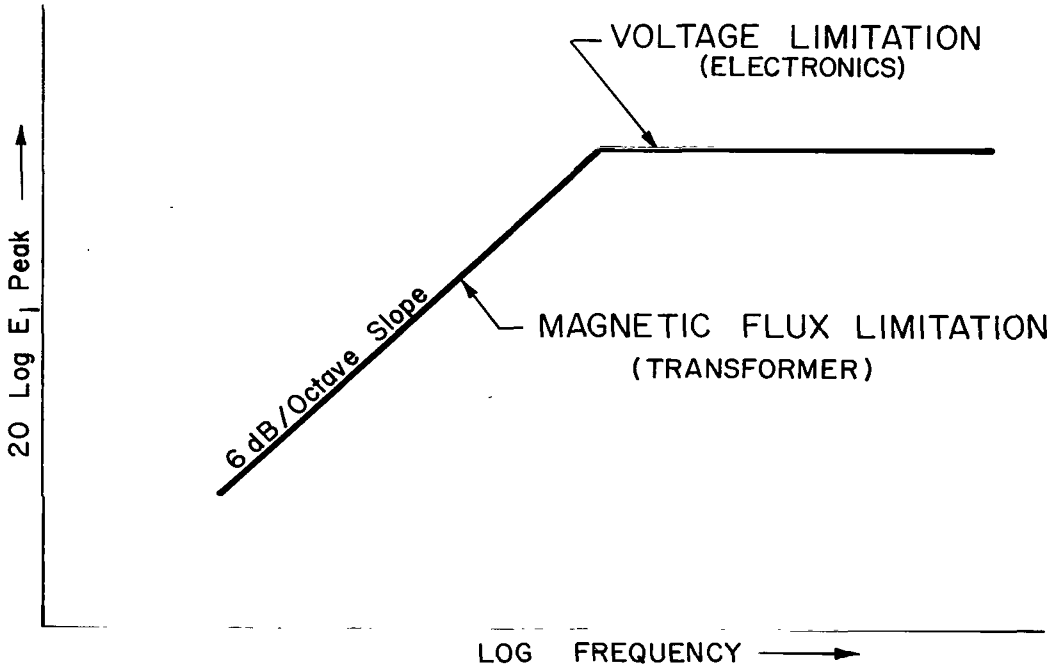

FIGURE 14. VOLTAGE LIMITATIONS OF THE AMPLIFIER DRIVING A TRANSFORMER

G. RANDOM SIGNAL CONSIDERATIONS

When the signal to be transmitted is a random noise of given spectrum, the two requirements given above must both be satisfied for peak values. Since RMS values of random noise are more definite and are available, a 15 db peak-to-RMS ratio is allowed which accounts for all but the most infrequent peaks. The requirements above are then converted to RMS values taking into account the 15 db peak factor. The voltage spectrum is integrated to give E/f in bands and a new RMS value E/r for the sum of the bands is obtained. In practice, the anticipated noise spectrum is given in terms of sound pressure level (SPL) and not in terms of the voltage spectrum. However, the following procedure can be used to calculate the maximum allowable value of the overall noise voltage:

a. From a given sound pressure level spectrum obtain an integrated spectrum (SPL - 20 $\log_{10}f$), where SPL is short-hand for the sound pressure level in each frequency band.

b. Obtain the overall RMS value of the integrated spectrum.

c. Identify a new ordinate for the integrated spectrum by setting the overall value of the integrated spectrum equal to $\frac{E_{1\phi}}{f}$ (in dbv) minus 15..

d. Obtain the difference in db between the overall SPL and the overall integrated SPL and calculate:

$$E_{1,\text{RMS}\ \phi} = \frac{E_{1\phi}}{f} - 15 + \text{OA SPL} - \text{OA (integrated SPL)},$$

where

E_{1}, $\text{RMS}\ \phi$ and $\frac{E_{1\phi}}{f}$ are given in dbv.

e. Obtain from the amplifier the maximum voltage E_{1m} in db re 1 volt and subtract 15 db, or

$$E_{1,\ \text{RMS}} = E_{1m} - 15 \text{ in dbv.}$$

The maximum RMS signal in dbv which can be transmitted for the given spectrum is the smaller of the two quantities, $E_{1,\ \text{RMS}\ \phi}$ or $E_{1,\ \text{RMS}}$. From knowledge of the microphone sensitivity, the gain of the preamplifier is set such that $E_{1,\ \text{RMS}\ \phi}$ and $E_{1,\ \text{RMS}}$ are not exceeded.

As an example, this precedure is applied to two Saturn noise spectra (Figures 5 and 9, Ref. 1) and reproduced in Figures 15 and 16. Consider a transformer for which

$$20 \log_{10} \frac{E_{1\phi}}{f} = -5 \text{ dbv (peak)}.$$

From Figure 15, the overall value of the integrated sound pressure level spectrum is about 122 db. This corresponds to -5 -15 = -20 dbv.

Since the overall sound pressure level is 143 db, the maximum safe voltage level for the transformer is $E_{1,\ \text{RMS}\ \phi} = -20 + 143 - 122 \doteq 0$ dbv, or about 1 volt RMS. Analogous calculations for a different rocket noise spectrum shown in Figure 16 lead to a maximum safe RMS voltage level of $E_{1,\ \text{RMS}\ \phi} = +5$ dbv using the same transformer.

It should be noted that in these examples this analysis provides voltage values which are slightly high because we have not included the spectrum content below 2 cps, which would reduce the value of $E_{1,\ \text{RMS}}$ that can be transmitted. In other words,since

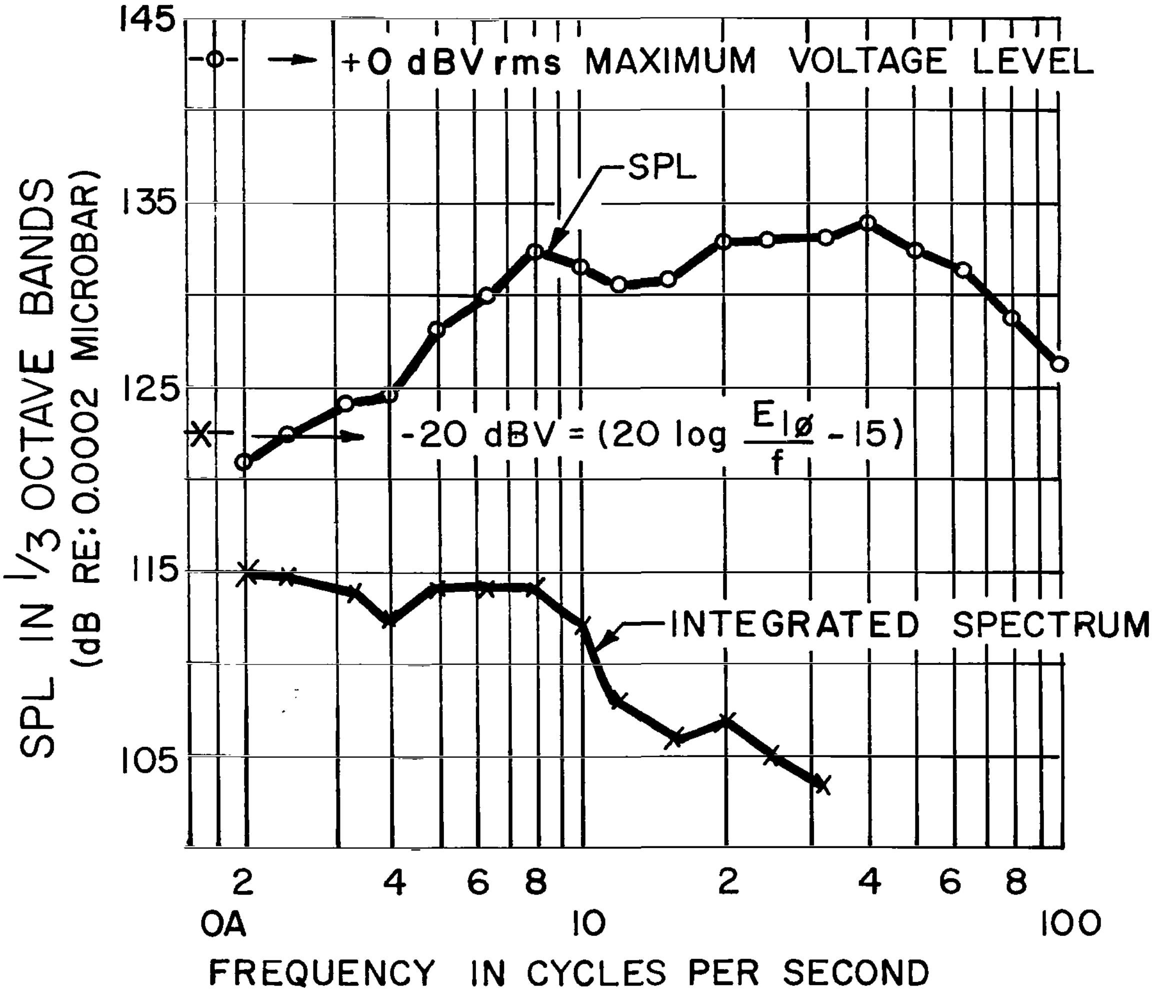

FIGURE 15. SAMPLE CALCULATION OF THE MAXIMUM RMS VOLTAGE WHICH CAN BE TRANSMITTED BY A TRANSFORMER. GIVEN $E_{1\phi}$ = -5 DB

in the present case the transducer and electronics are capable of transmitting down to 1 cps, the spectrum at 1 cps should also be included in the calculations. Also, it should be kept in mind that if the system is to be used to measure the noise of large boosters, such as the S-IC, new values of maximum voltage levels should be determined from measured or estimated noise spectra.

H. LINE AMPLIFIERS

The line amplifiers at the transmitting end serve three purposes:

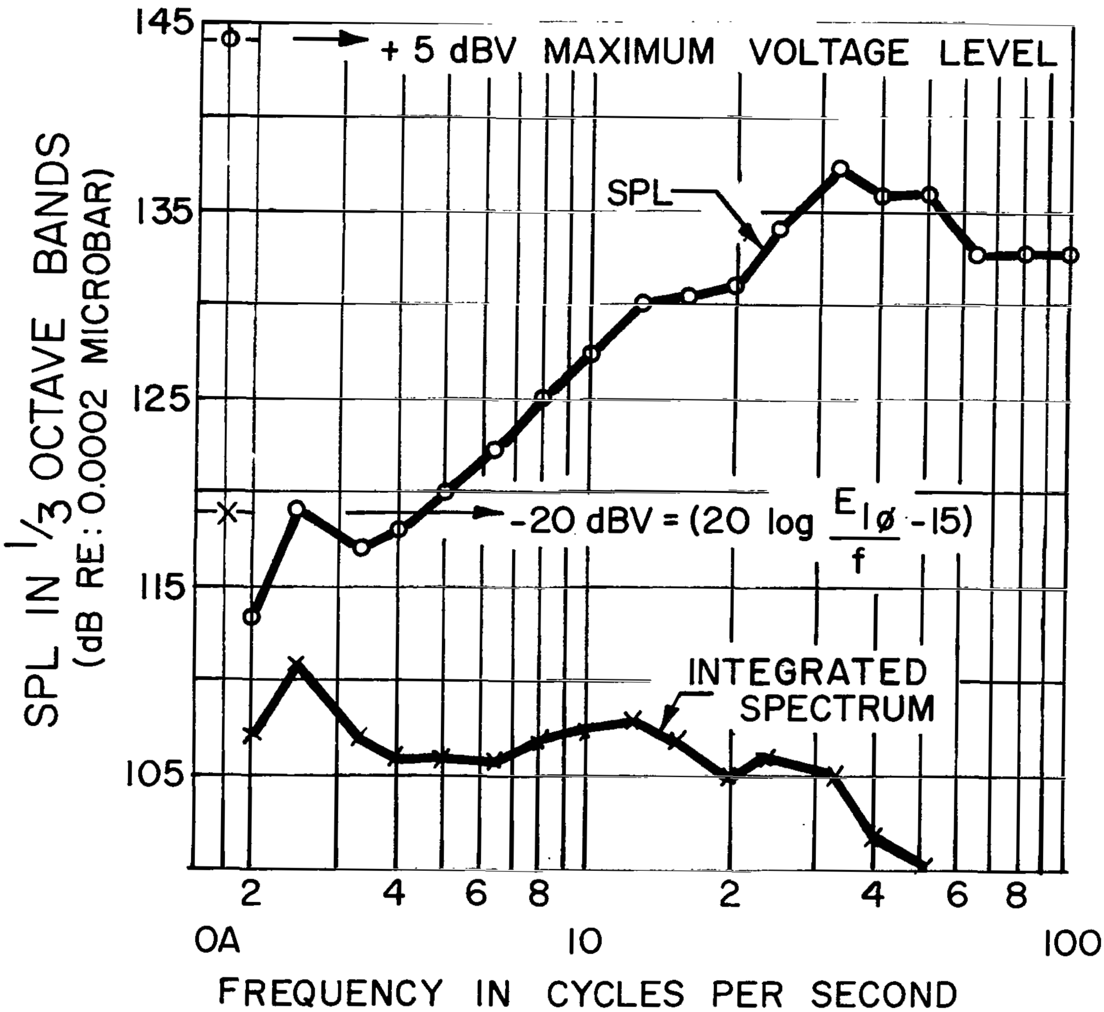

FIGURE 16. MAXIMUM RMS VOLTAGE WHICH CAN BE TRANSMITTED BY THE SAME TRANSFORMER FOR A DIFFERENT SPECTRA (SECOND SAMPLE CALCULATION)

1. Isolate the line capacitance from the transformer leakage inductance which would otherwise produce unwanted resonances.

2. Provides a high-impedance termination for the transformer.

3. Provides the necessary signal power to the transmission line.

Each line amplifier consists of a pair of complementary transistors which supply the signal power to the transmission line. There is one floating amplifier in each leg of the line. The four transistors form a balanced circuit and should not affect the common mode rejection characteristics of the transformer in most installations.

The complementary pairs operate near class B with a collector current of approximately one milliampere per pair. For large signals the complementary pair can deliver a current in excess of 15 ma. This operation requires a low-impedance power supply which is provided by a dry-cell battery. In the absence of signals, the dc power drain from the battery is slightly over 25 milliwatts, or about 2 ma at +9 volts. With normal noise signals transmitted, the battery power drain will be less than 100 milliwatts. The circuit diagram is shown in Figure 17.

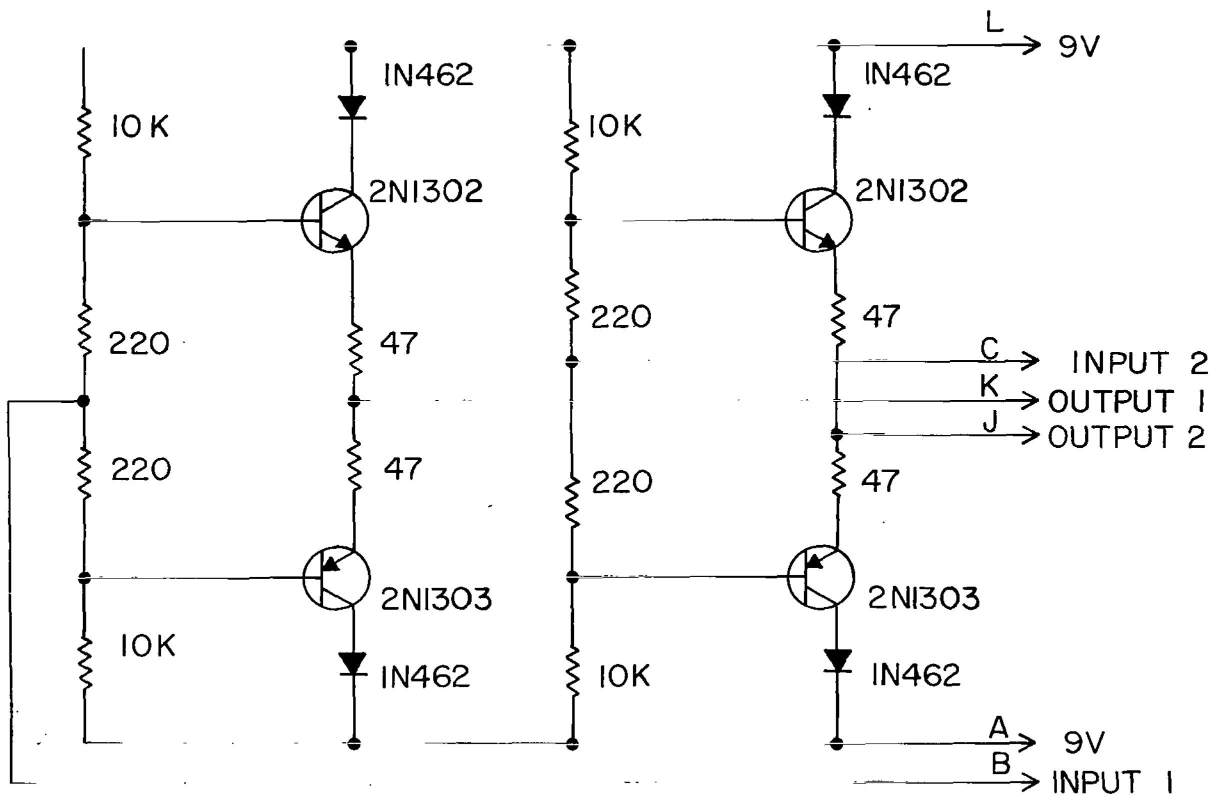

FIGURE 17. SCHEMATIC OF LINE AMPLIFIER CIRCUIT

An identical pair of line amplifiers is installed at the receiving end of the line. The line amplifiers at the receiving end serve three purposes:

1. Isolate the line capacitance from the transformer leakage inductance which would otherwise produce unwanted resonances.

2. Provide a low-impedance source for the transformer.

3. Provide the necessary magnetizing current to the transformer.

The circuit diagram is identical except that, for practical reasons, rechargeable nickel-cadmium batteries are used.

I. SIGNAL CONDITIONING CIRCUIT

Figure 18 shows a circuit diagram of the Signal Conditioning Unit which follows the line output transformer. It contains a 50 db step-attenuator which is adjustable in 5 db steps, followed by a field-effect transistor input stage and a solid-state

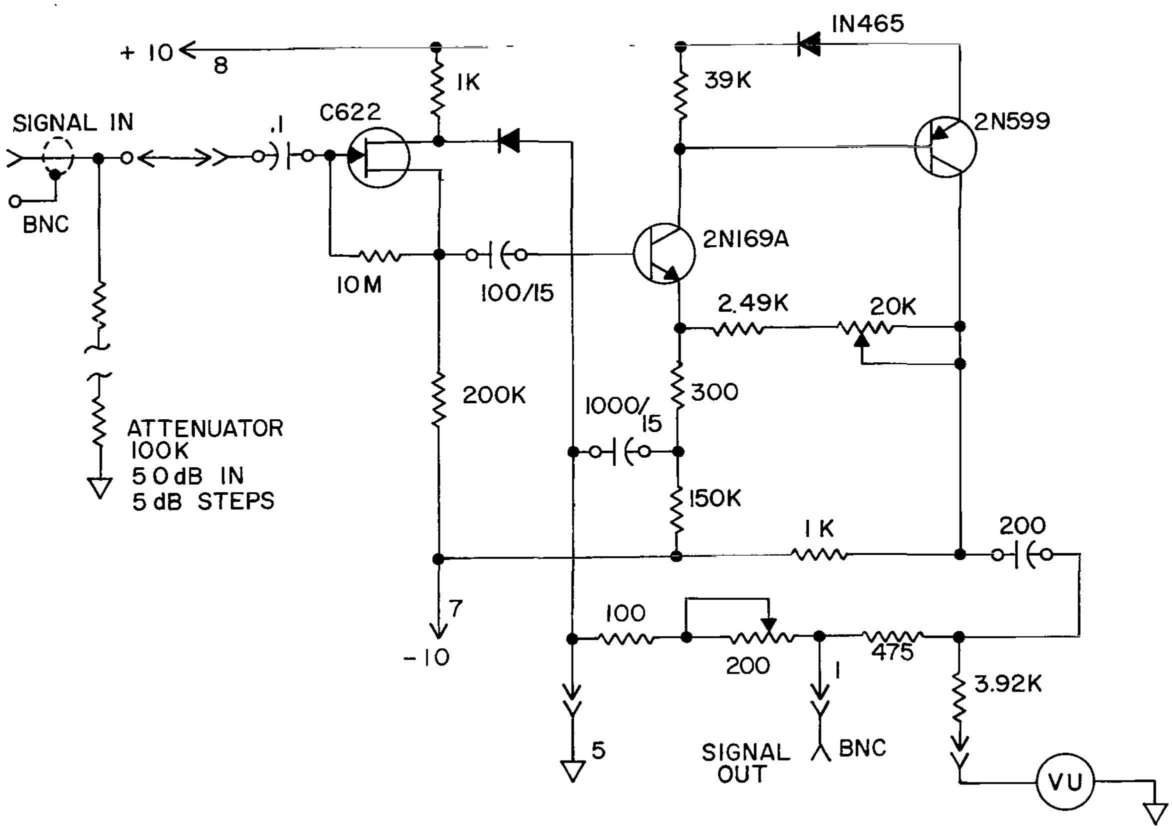

FIGURE 18. SCHEMATIC OF SIGNAL CONDITIONING CIRCUIT

buffer amplifier of about 10 db voltage gain. A VU meter is provided to monitor the output voltage to the tape recorder. This recorder is a 14-channel magnetic instrumentation recorder which meets IRIG standards for FM recording [Ref. 2].

The amplifier design also provides a normalization feature permitting the signal level of a particular channel to be normalized. The usual procedure is to adjust the individual channels for full scale levels for any desired reference SPL at the microphone.

For this condition, the channel can be adjusted for zero VU at an output signal level of 400 millivolts, RMS. Because instrumentation tape recorders are usually calibrated for 100 per cent modulation, the channel dynamic range is thus established to be 35 db below any arbitrary reference value of SPL. Considering that the range of noise spectra can often approach this value, it is obvious that care must be taken to normalize the measurement channels to obtain the best performance from the system.

SECTION VI. PACKAGING, ADJUSTMENTS AND CONTROL CIRCUITS

A. FIELD UNIT

Figure 19 shows the diagram of the Field Unit, MSFC 1162-T, consisting of Preamplifier, Decade Amplifier, Line Amplifiers, and associated circuits, connectors, and batteries.

The electronics are assembled in three plug-in printed circuit boards which, in turn, are mounted on a chassis assembly containing the necessary attenuator, transformer, terminals, relays, and battery packs. A magnetic latching relay under the command of an additional field line acts as an On-Off switch.

Figure 20(a) shows the bottom view of the transmitter chassis with the shield removed. The three printed circuit cards and the dry-cell batteries are clearly visible. Figure 20(b) shows an interior view with the front of the transmitter chassis opened. Figure 20(c) shows the chassis with the shield replaced.

The transmitter chassis itself is placed in a waterproof metal box for field use. Figure 20(d) shows the Field Unit with the box open. The front panel of the transmitter chassis and the controls, jacks, and binding parts are clearly visible.

B. LINE UNIT

Figure 21 shows the diagram of the Line Unit MSFC 1162-R, consisting of Line Amplifier BBN-552A, and associated circuits, connectors, and rechargeable batteries. The electronics are assembled on one plug-in printed circuit board, which is mounted on a chassis assembly containing the necessary attenuator, transformer, terminals, relays, and battery packs. The chassis, and slides, occupies 5-3/4 inches of

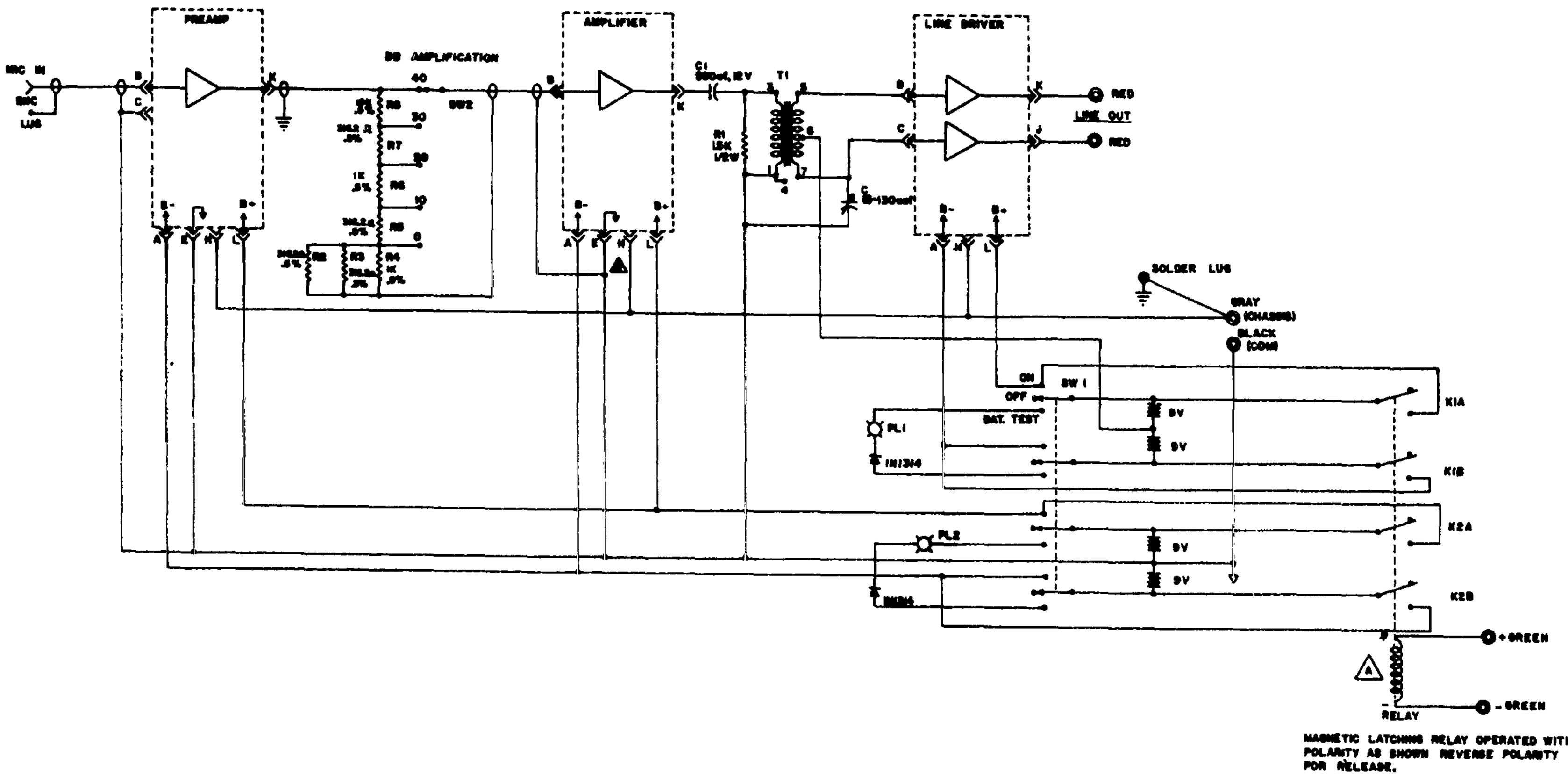

FIGURE 19. INTERCONNECTION DIAGRAM OF FIELD UNIT, MSFC-1162-T

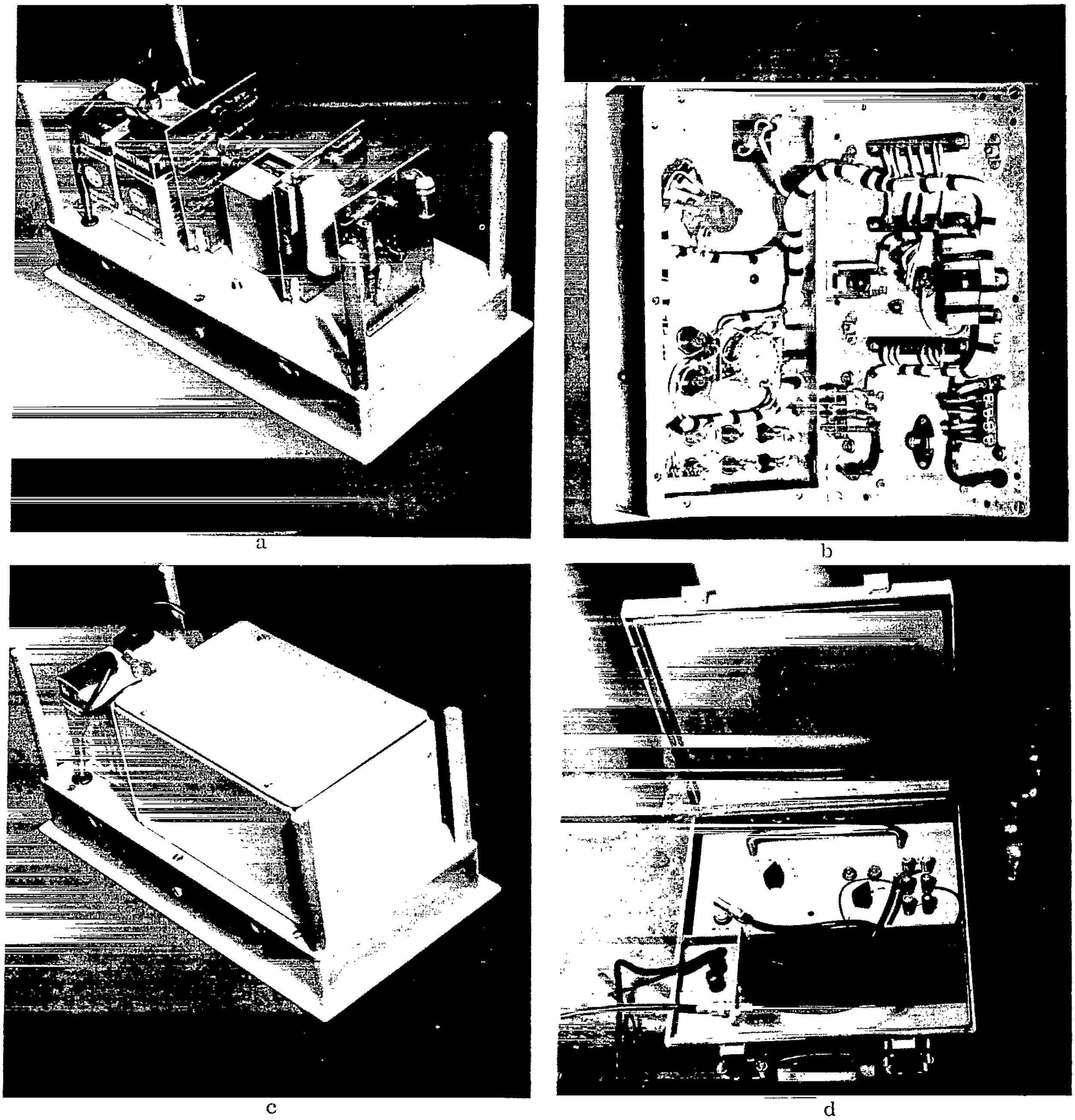

FIGURE 20. (A) VIEW OF FIELD UNIT SHOWING CIRCUIT BOARDS, TRANSFORMER, AND BATTERIES; (B) INTERNAL WIRING OF FIELD UNIT; (C) BOTTOM VIEW OF FIELD UNIT SHOWING COMPLETE CHASSIS; (D) TYPICAL FIELD INSTALLATION

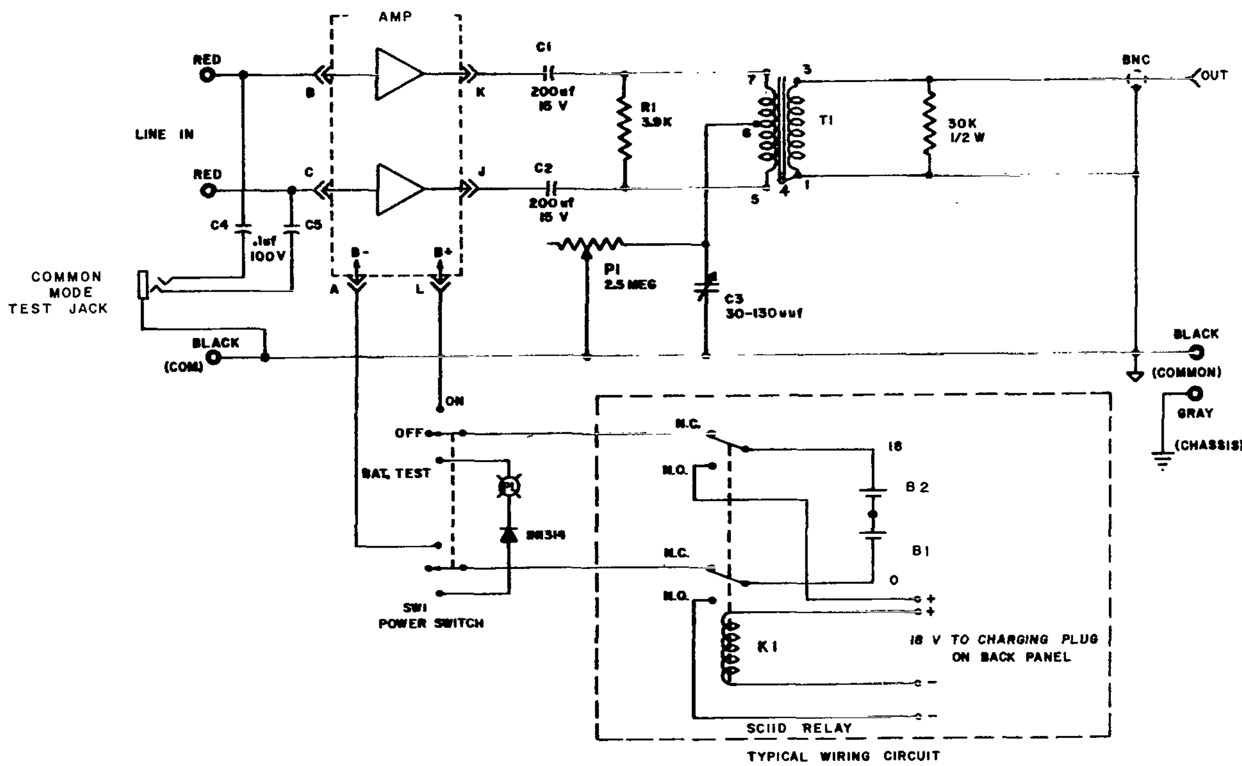

FIGURE 21. INTERCONNECTION DIAGRAM OF LINE UNIT, MSFC 1162-R

panel space. The front panel has the "on-off-battery-test" switch, indicator, the common mode test jack, and common mode suppression adjustment. The line units are mounted in groups of seven in the recording facility. Figure 22 shows such a group of seven line units with the top cover removed.

The most critical function of the line unit is to reject, at its output, signals which are common to both sides of the transmission line and constitute, therefore, interfering noise. This common mode rejection depends primarily on the transformers, which were designed to provide good rejection to at least 10 kcps. To improve the common mode rejection of the complete circuit at the high frequencies, a compensating network was provided, consisting of a variable resistor R_1 and capacitor C_3 (Fig. 21).

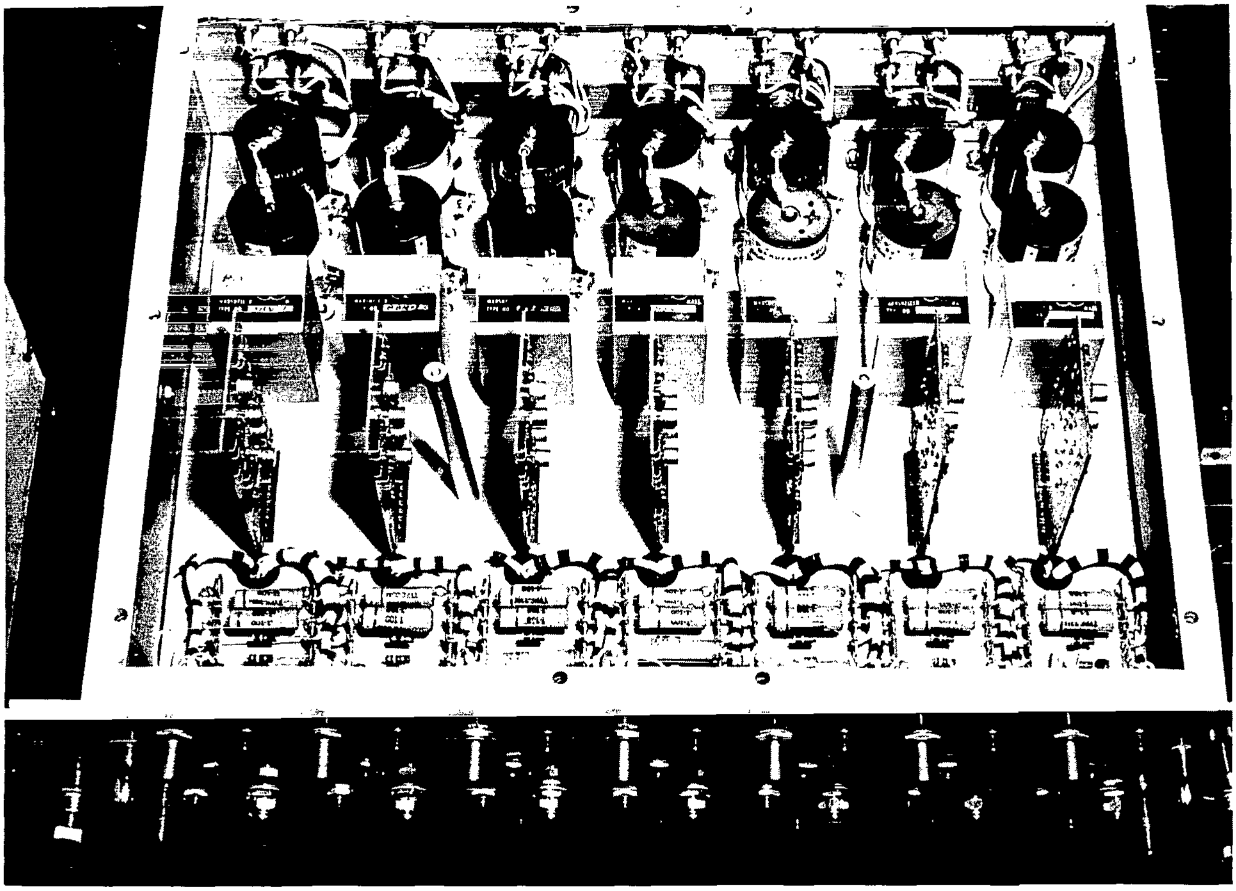

FIGURE 22. VIEW OF LINE ASSEMBLY WITH TOP REMOVED

When a generator is plugged into the common mode test jack, an interference voltage is thereby simulated. By adjusting P_1 and C_3 for minimum output voltage at the BNC output terminal, a common mode rejection of at least 80 db can be achieved at all frequencies up to 10 kcps.

A charging jack is also provided to plug in a 28 volt dc external power supply for recharging the batteries. When the external voltage is applied, relays are energized which connect the batteries, through limiting resistors, to the charger. By charging the batteries every night, the equipment is always ready for use during the day.

C. SIGNAL CONDITIONING UNIT

The Signal Conditioning Units are mounted in groups of seven in the recording facility. Each unit is mounted on a sliding chassis occupying seven inches of panel space. The step attenuator and VU meter are mounted on the front panel. The signal connections are made from the rear. Normalization controls are accessible from the top when the chassis is pulled out. Power is provided by electronic dc power supplies.

Figure 23 shows a group of seven Signal Conditioning Units.

Figure 24 shows the complete installation.

SECTION VII. CONCLUSIONS

The system described in this report has met almost all design requirements and is currently used extensively in the field with success. It is weather-proof, can be installed with a minimum of manpower requirements and the field units can be left outdoors unattended for long periods of time. It is independent of external power sources. Only one pair of field wires are required to carry the signal from the field unit to the central recording station. Another pair of field wires control the On-Off switch. Maintenance is accomplished with a minimum of down-time; in most cases replacing the printed circuit boards or the batteries is all that is required.

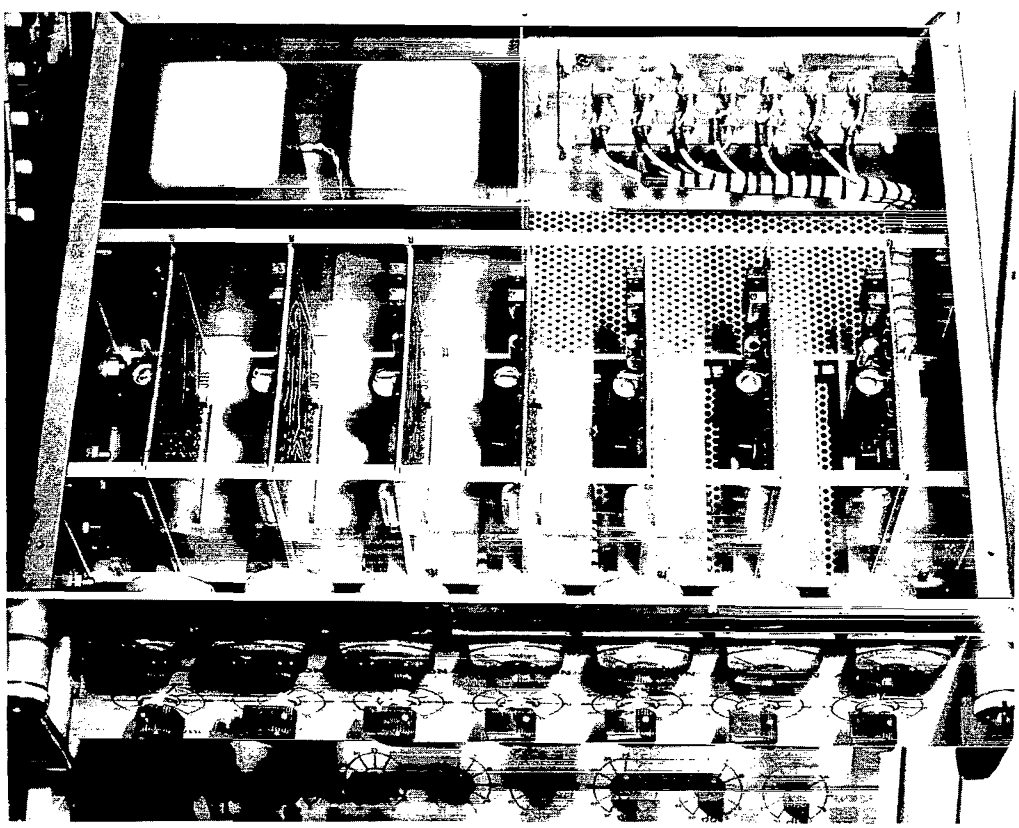

FIGURE 23. SIGNAL CONDITIONING AMPLIFIER ASSEMBLY WITH TOP REMOVED

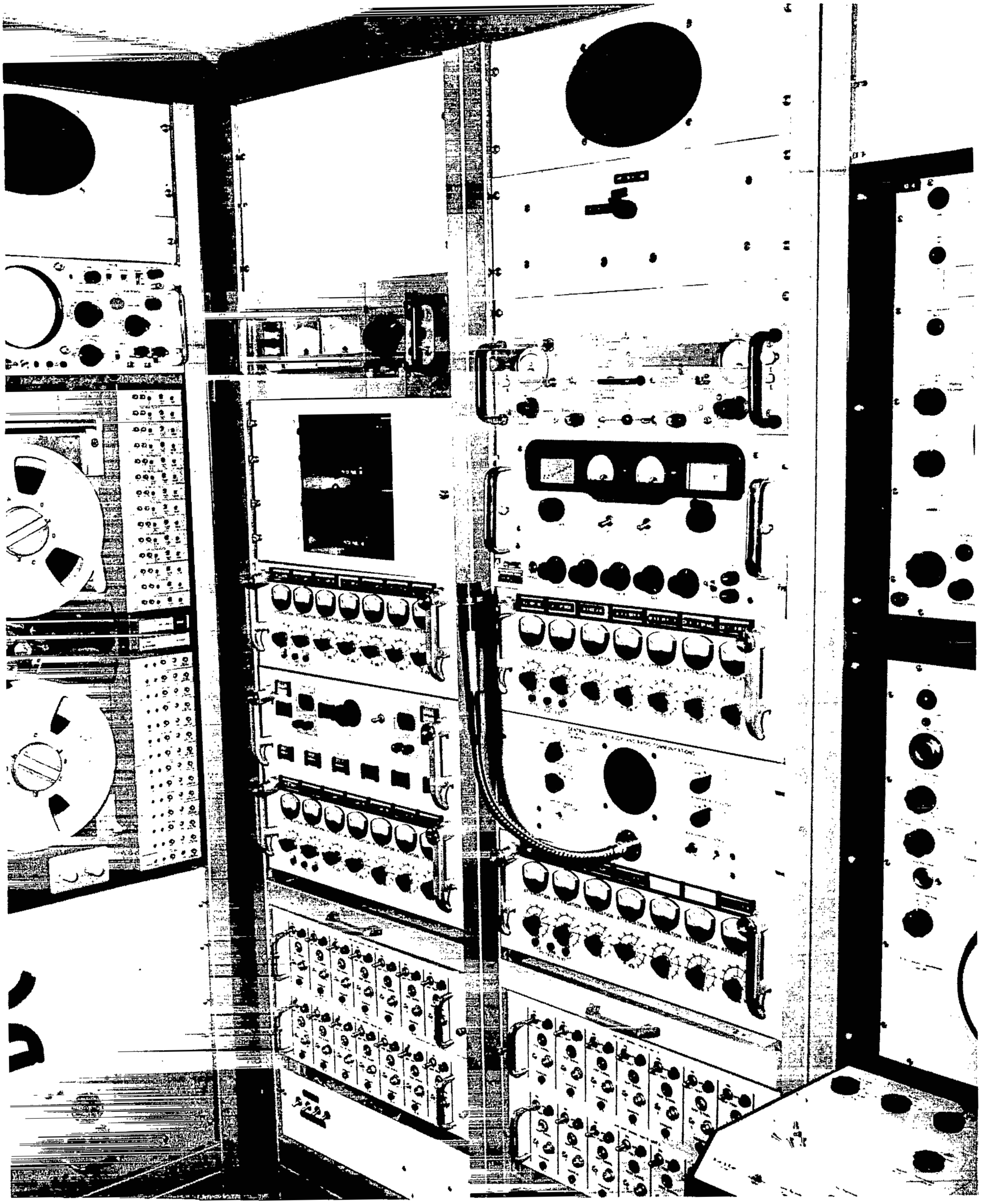

FIGURE 24. TYPICAL SYSTEM INSTALLATION

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1. Dorland, W. D., "Far Field Noise Characteristics of Static Tests of the Saturn Booster," NASA TN D-611, September 1961.

2. IRIG Document 106-60, "Telemetry Standards," November 1960.

NASA-Langley, 1964 M753

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